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THE OCCURRENCE AND SIGNIFICANCE

OF

BORNITE

by

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PART I

GENERAL INTRODUCTION

PART I.

GENERAL INTRODUCTION

Importance of the Subject

In dealing with the numerous problems connected with a comprehensive geologic study of the sulphide ores of copper, it has been found that some of the most intricate and puzzling questions encountered are those associated with the mineral bornite. In the case of the other ore-minerals, the relations observed either in the field or under the microscope are as a rule relatively simple and constant, and generally yield a definite but limited amount of information. Bornite, however, exhibits under diverse conditions a variety of features and a complexity of relationships which are difficult of interpretation, but which are of great significance when understood. The questions which arise concerning this mineral range from broad problems demanding knowledge of the field relations to intimate queries concerning the details of intricate microscopic structures, and an appreciation of the critical evidence which is offered by associations and properties of bornite is often necessary before a satisfactory understanding of the nature of certain ore-bodies can be obtained. A clear conception of the genesis of the ore can often be obtained from the relations of the bornite to other primary sulphides and to the gangue minerals, and the effects of superficial agencies are invariably recorded in the bornite with far greater delicacy

Chapter I

Introduction

Definition of the Problem

and completeness than in the other sulphides. Apart from the scientific value of detailed knowledge of the position occupied by bornite in the processes of primary mineralization, the richness of bornite as an ore of copper makes any information especially welcome which would lead to a more accurate comprehension of the habits and distribution of the mineral and which would direct prospecting and development work most intelligently. The study of secondary[1] ores derived from bornite presents another field which offers many open problems of both scientific and practical worth. The economic value of a correct judgment concerning the secondary or primary nature of a chalcocite ore makes it of great importance to seek all means by which the necessary information can be gained. In most deposits, chalcocite ores are believed to be of secondary nature, and all plans for their development are based upon the expectation that they will pass into leaner primary material at relatively shallow depths. In the deposits in which the nature of the chalcocite is in question, the mineral has been found almost invariably to be in close association with bornite, and the problems of its origin have resolved themselves largely into studies of its relations to this mineral.

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1. Throughout this paper the terms primary and secondary are used only in their geologic sense. The former is reserved for processes and products associated with the original mineralization; the latter for processes and products dependent on superficial alteration.

It has therefore been considered desirable to ascertain by all available means the facts concerning the occurrence and relations of bornite, and to gain an understanding of their significance. To do this has been the object of this investigation.

Although many of the broad features of bornite ores have been recognized for many years, the recent application of the metallographic microscope to the study of opaque minerals has revealed so many unsuspected relations that very little of the older literature concerning the paragenesis of bornite can be accepted without reservation. Consequently, with the exception of the work of a few recent investigators, the study of the relations of bornite by modern microscopical methods opens an almost new field in which thorough exploration is fully justified by the promise of results of both scientific and economic value.

Statement of the Problems

From both a scientific and an economic standpoint, the chief problems associated with the deposits studied may be divided into two groups:

(1) those concerned with the nature of the primary mineralization and

(2) those concerned with the character of the secondary alteration.

In the first group, the establishment of the range of conditions under which bornite may form is the most general prob-

lem, and all others are units leading to its solution. In the case of each deposit, knowledge must be obtained concerning the form of the ore-bodies, their relation to the neighboring rocks and structural features, and the position of bornite in the sequence of gangue and ore-minerals. From the interpretation of the evidence afforded by these points and others, the genesis of the deposit may be inferred in most cases with reasonable certainty.

The second group of problems, viz. those related to the secondary changes due to the superficial alteration of an ore-body brings up a greater number of queries. The determination of the importance of bornite as a product of surface processes is one of the most definite problems which has been encountered. The suspicion in many mining camps that the bornite ores are of secondary origin emphasizes the value of positive information on this point and it is believed that evidence of a final nature is presented in these studies. The distribution of the secondary sulphides, the depth to which enrichment can extend in bornite ores, comparisons of similar influences on pyritic and other ores, and the influence on the alteration of bornite of numerous factors such as climate, physiography, wall rock, rock alteration, and structure all offer problems depending largely upon field observations for solution. On the other hand, the degree of replacement by secondary sulphides which the bornite has suffered, the relative ease of bornite en-

richment compared with the other sulphides, and the relations between the various ore and gangue-minerals are questions which are most definitely settled in the laboratory. The microscopic relations of chalcocite to bornite offer a great number of important problems, among which the most important are the interpretation of the "lattice structure", in which the chalcocite penetrates the bornite as a regular grill of intersecting lines or the "graphic structure", in which the two minerals are associated in eutectic like patterns on the polished surface. In seeking the meaning of these difficult relations, numerous minor features, such as residual "spines" of bornite in chalcocite, rims of bornite about partially altered grains, "halos", and "hazy boundaries" all demand their share of attention, and add the weight of their evidence to the general attack on the problems of bornite alteration.

The important question of primary chalcocite is closely bound up with the interpretation of the various relations between chalcocite and bornite. The deep enrichment in bornite ores, the inheritance of bornite structure by chalcocite, the two etch patterns in chalcocite, and the origin of the lattice and of the graphic structures are points which must be understood before a final verdict can be given. The economic importance of the problem is obvious. Experience in many camps has shown that the rich chalcocite ores are usually of secondary origin, i.e.

formed by the action of meteoric waters descending through the deposit from the surface. Consequently they are expected to give way at relatively shallow depths to leaner primary sulphides, which may possibly be too low in copper to be worked profitably. If, however, it can be established from a study of the relations between the sulphides on the upper levels, that the chalcocite is a primary constituent of the ore, its continuance with depth would be expected, and all plans for the development of the deposit would be influenced by this knowledge. If the chalcocite is secondary, it becomes of economic importance to be able to predict the nature of the change where the superficial sulphides yield to the primary ores. If it can be determined that the chalcocite is largely a replacement of bornite, the decrease in copper per centage of the ore will be relatively small, and will ordinarily permit profitable operations to be carried into the primary ore; if, however, the chalcocite is a replacement in part at least, of pyritic material, the decline in value is much greater and may not allow the profitable mining of the deeper ore. Although evidence on these points may be gained by drilling or other exploratory methods, it is believed that in many cases reliable conclusions may be gained at less expense from microscopical studies of samples from the upper parts of the deposits.

Treatment of the Subject

The accuracy of any conclusions of general nature which may be drawn, depends directly upon the degree to which the material selected as a fair sample of all occurrences, and consequently the attempt has been made to include among the deposits studied, examples from all types of ores in which bornite is an important mineral. The deposits chosen for detailed investigation include several in which the bornite is believed to be of either magmatic or pneumatolytic origin, others considered to be typical examples of contact-metamorphic ores, and certain deposits regarded as products of various phases of hydrothermal action. In addition the camps selected are situated in widely separated regions, consequently their ores have been subjected to sufficiently diverse climatic and physiographic influences to offer as great a range in conditions affecting the development of secondary sulphides as is necessary to insure the general application of the relations observed.

Before the main part of the paper is presented, a short discussion is given of some features of general mineralogical interest in connection with bornite. A brief historical account of the mineral is presented with a summary of older analytic and synthetic work, which although of little present value, is of some interest as a record of the difficulties caused by unsuspected impurities

in the materials available for study.

The descriptions of a series of ore-deposits in which bornite plays an important part, either as an ore-mineral or as a signigicant factor in their history, form an important part of paper. Where definite problems can be handled in the case of individual deposits, they will be considered there; if more general evidence is required for their solution, they will be reserved for the later chapters in which knowledge from the whole field may be brought to bear upon them. The different deposits are treated with various degrees of thoroughness. In cases in which the field work and collections offered new and more definite information than had been previously published, the details are given at greater length than for those deposits in which the investigation is limited to a study of older collections, or merely to the literature. A few especially interesting deposits, such as those at Engels, California and at Kennecott, Alaska, have been described more fully than many of the others, but their unusual features are believed to justify the prominence given them. Other important deposits, however, such as those at Butte, Montana, and Bisbee, Arizona, have been dealt with very briefly, even though their ores present many of the most intricate problems associated with bornite. The chief features of the great ore-bodies, however, have already been given a prominent place in the literature, and the time available was too

short to make a study of the field conditions which would add any additional knowledge of value. The handicap of being forced by lack of time to slight these important deposits is greatly offset, however, by reliable information that is available from recent work by other investigations. A detailed paper on the Bisbee ores, based on an intimate knowledge of both field and microscopical relations supplies valuable data which may be accepted without question, and intensive studies of Butte material which are being carried on in this laboratory constantly add trustworthy evidence on the problems presented by those deposits.

The order in which the camps are described is based in a broad way upon the interpretation of their origin. The ores which are believed to be most closely related to magmatic conditions are discussed first; they are followed by the contact-metamorphic deposits, and later by descriptions of ores formed under various stages of hydrothermal action. The descriptions are thus arranged according to decreasing intensity of primary conditions of origin, but on account of the complex and transitional nature of some of the deposits, their grouping must be somewhat arbitrary. For example, the Engels ore-body furnishes evidence of sulphides formed under varying conditions from pneumatolytic to late hydrothermal, but on account of the greater interest attached to the earlier products, it is presented with the pneumatolytic deposits, although the larger part of the

commercial ore was formed under hydrothermal conditions.

In the fourth section of the paper, the important primary relations of the bornite ores are discussed, and the common properties and general range of genetic conditions favorable for the production of bornite are emphasized. A second divison of this section is concerned with the problems associated with this alteration of bornite, such as the relative ease of replacement by chalcocite, the field distribution of the chalcocite, and the significance of the different types of replacement structures. The final divison of the section is devoted to the much debated question of the primary or secondary origin of the chalcocite in the graphic structure with bornite. The evidence and the various arguments are summarized, and two explanations are proposed. The paper closes with a summary of the results and conclusions in individual cases and in general.

Field and Laboratory Work, and Acknowledgements

The work of this investigation of bornite ores has extended over a period of about two years, but the time has been somewhat diminished by other smaller problems and academic duties. During two summers in the field, attention has been largely directed toward the occurrences of bornite. A large fraction of the other months have been consumed in laboratory studies of the material and information gathered.

The work embodied in this paper is part of an ex-

tensive study of the sulphide ores of copper which is being carried on by the Secondary Enrichment Investigation, and consequently a wider range of information was available upon which arguments and conclusions could be based than the special field emphasized in direct connection with the problems of bornite.

The deposits near Kennecott, Alaska, were visited in the summer of 1915, in the company of Messrs. L. C. Graton and A. M. Bateman. The larger part of the time was spent in studying the great chalcocite ore-bodies of the region in which bornite is a small but very significant constituent, and a short time was available for a study of the smaller chalcopyrite-bornite deposits in the greenstone of the neighborhood. In addition to material collected in 1915, specimens and information from parts of the region I was unable to visit have been placed at my disposal by Mr. Alfred Wandtke to whom I owe my sincere thanks.

A broader range of country was covered in the summer of 1916, and a valuable collection of material was obtained from most of the important camps in western United States in which bornite is a noteworthy ore-mineral. The list of mines and districts in which the occurrence of bornite was especially studied in 1916 includes: Engels, Plumas Co., California; Marble Bay Mine, Texada Island, B. C., the Similkameen district, British Columbia; the Boundary District, British Columbia and Washington; Butte, Montana; the Ever-

green Mine, Gilpin Co., Colorado, and Bisbee, Superior, and Morenci, Arizona. Visits were also made to the following camps in which bornite is of minor importance: Rossland, B. C., Bingham and Tintic, Utah; Ely, Nevada; Tularosa, Tyrone and Santa Rita, New Mexico; and Jerome, Ray, Miami, Globe, and Morenci, Arizona. A considerable part of the expenses of the work were covered by a Sheldon Traveling Fellowship from Harvard University. In several of the most important camps, the field observations were made in the company of Messrs. L. C. Graton and A. Locke, and from their intimate knowledge from the results of previous work of the Investigation, I gained a far clearer conception of the field conditions than could have possibly been obtained in any other way. In all places the hospitality, characteristic of the mining profession, expressed itself in the kind efforts that were made to give me all opportunities to study the mine workings, and to acquaint me with the local features of geologic importance. Especial thanks are due to Messrs. Stephen Birch, W. H. Seagrave and H. D. Smith of the Kennecott Copper Corporation for many courtesies extended during our work in Alaska in 1915; to Mr. John Reinmiller at the Engels Mine, California; to Mr. A. F. Eastman of the Tacoma Steel Co., to whom I owe the privilege of visiting the Marble Bay Mine on Texada Island; to Messrs. Patrick Crane and H. E. Doelle of the British Columbia Copper Company, whose guest I was for several days on Copper Moun-

tain near Princeton, B. C., and at the Mother Lode Mine; to Messrs. C. F. Martin and Nelson at the Granby Companies' properties at Phoenix, B. C.; to Mr. G. S. Trombley, whose cabin I shared on the slopes of La Fleur Mt. in the Boundary District, a few miles from the line in Washington; to Messrs. Arthur Linforth, D. A. Hall and other members of the geological staffs at Butte, Montana; to Professor H. B. Patton of the Colorado School of Mines at Golden, with whom I spent two enjoyable and instructive days on a trip to the Evergreen Mine in Gilpin Co., Colorado; to Messrs. Y. S. Bonillas and Leon Fenchère of the Copper Queen Mining Co., at Bisbee and Mr. Ira B. Joralemon of the Calumet and Arizona Mining Co., at Warren, Arizona, who kindly showed me the most interesting parts of their ore-bodies in connection with my problems; and to Messrs. W. C. Browning and I. A. Ettlinger of the Magma Copper Company at Superior, Arizona. To many others at the various camps visited, I am indebted for many courtesies, for which I wish to express my thanks.

I am indebted to Mr. Joseph Murdoch for many excellent photographs of bornite structures, which were made by him during his work on the staff of the Secondary Enrichment Investigation, and also to Mr. W. L. Whitehead for several photographs of material from the Engels Mine.

My thanks are especially due to Professor L. C. Graton for the thoughtful and valuable criticism that he has given all parts of this work, both in the field and in the

laboratory, and in connection with the preparation of the manuscript, for which I am very grateful.

PART II

MINERALOGY OF BORNITE

PART II. MINERALOGY OF BORNITE.

History

The existence of "copper pyrites" has probably been known since the metal was first won from sulphide ores, but the similarity in color between bornite and chalcopyrite when they are tarnished made their separation into distinct mineral species uncertain almost until modern times. There is evidence, however, that the identity of bornite was suspected as early as 1546, for Georgius Agricola in his famous work De Natura Fossilium printed in that year, mentioned two minerals, "Pyrites aurei colore" and "Pyrites aerosus", which may be correlated fairly certainly with chalcopyrite and bornite. The distinction of the tarnished variety of "copper pyrites" by a separate name is significant, and warrants the addition of bornite to the long list of minerals first recognized by Agricola.[1]

Appreciation of the distinct character of bornite is probably found in Johann Friedrich Henckel's "Pyritologia" or "Kies-Historie", published in Leipzig in 1725, but the vagueness of his statements and the variable application of the names he uses, makes his contribution even less definite than the descriptive terms employed by Agricola. The sentences containing

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1. The source of information concerning Agricola and his works most easily available is the excellent translation of De Re Metallica (1556) by Herbert Clark Hoover and Lou Henry Hoover (London,1912). On page 109, a summary of minerals in De Natura Fossilium is given.

the probable reference to bornite are most satisfactorily given in his own language, and are as follows: - - Kupffer-glass ist noch dunckler [than Fahlerz, previously described] und neiget sich gar zur Schwärtze, aus Ursachen, weil es sehr Eisenschüssig ist, dergleichen mir von den zwölff Schlüsseln bekannt; und Kupffer-Lasur nimmt sich nebst seiner dunckeln Farbe mit seinen stahlblauen Farben aus, wiewohl der Missbrauch auch eingeführet hat, ein sonst gelb-grünlichtes Kupffer-Erz, so nur auf Klüfften mit blauen Farben spielet, Kupffer-Lasur zu nennen, und es scheinet dass Kupfferglass bei den Alten keine andere Sache als Kupffer-Lasur bedeutet habe, sondern gleichwie aus Glasur Lasur, als aus Glasur auch Glass nach der allen Sprachen gemeinen von Geschwindigkeit in Aussprechen entstehenden Wörter Verkürtzungen, und Zusammenziehungen, entsprungen sei. [1] The mineral described by Henckel is

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1. Translation; Kupffer-glass [chalcocite?] is still darker [than Fahlerz, tetrahedrite, previously referred to,] and even tends toward blackness, because it has a high iron content due to causes which are known to me from the twelve keys [?]; and Kupffer-Lasur [probably bornite] has in addition to its dark color a steel blue shade, although the misuse has arisen of calling a usually yellow-green copper-ore, Kupffer-lasur which sparkles with a blue color only along fractures and it seems the Kupfferglass [chalcocite] among the ancients meant nothing less than Kupfer-Lasur, just as from Glasur, Lasur and from Glasur, Glass, originated from abbreviations and contractions common to all languages resulting from rapidity in speech. Johann Friedrich Henckel, Pyritologia, Leipzig, 1725, page 451.

classified as a member of the "Kiess-Rolle", and is therefore a metallic sulphide or arsenide, according to his definition. It is doubtful,however,whether the name Kupffer-Lasur was confined to this usage, for it is applied to the mineral azurite by slightly later writers.

The earliest publication in which names are given which clearly indicate that the mineral was commonly recognized at the time, is the Mineralogy by Johann Gottskalk Wallerius, printed in 1725. A description of bornite[1] appears in the Latin edition of 1778 under the heading, Cuprum, pyrite fuso mineralisatum, minera flavo fusca, and the following popular names are added:- Swedish, Lefeverslag, Gulbrun kopparmalm; French, Mine de cuivre hépatique; and German, Braunes kupfererz, or Leberschlag. In the French translation of Wallerius, by Paul Thiry, published in 1759, the mineral is referred to under the names:- "Mine de cuivre hépatique ou de la couleur du foye," with the latin terms, "cuprum sulphure, ferro mineralisatum, minera pyriticosa fulva; Minera cupri hepatica. The description is as follows:- "Elle est d'um jaune tirant sur le brun on d'une couleur pâle,

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1. Page 285. Colore est flavo fusco, reipsa pyrites fuscus (spec. 277) cuprum solutum continens parva quantitate; proprietatas pyritae fusci nonimati utplurimum retinens; a quibus haec minera cognosi et agnosci potest.

et étroitement unie avec du soufre et du fer; la substance est pyriteuse: il y a meme des Naturalistes qui la mettent au rang des pyrites; frappée avec l'acier, elle ne donne que peu ou point d'etincelles. On a (1) La mine de cuivre hépatique brune (Minera cupri hepatica fulva) Elle est de la couleur du foye; riche en cuivre, et d'une consistence tantôt serrée tantot peu compacte. (2) La mine de cuivre hépatique pale. (Minera cupri hepatica livida.) Elle est presque blanche et pale comme de l'étain, d'une couleur foncée, et d'un brun tirant sur le bleu; interieurement elle paroît composée de grains, mais exterieurement elle semble feuilletée.[1] The various tarnished colors of the bornite are probably the cause for the subdivision of the species, but another mineral may be meant by the second description.

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1. Translation. It is of a yellow color, tending toward brown, or a pale color, and intimately united with sulphur and iron; the material is pyritic: there are even some Naturalists who place it in the group of pyrites; struck with steel it gives only a few sparks or none at all. We have (1) the liver brown copper mineral. It is the color of liver, rich in copper, and of a dense to slightly compact texture. (2) The pale liver-colored copper mineral. It is almost white and as pale as tin, of a warm color, and of a brown, turning toward blue; internally it appears granular, but on the outside it seems foliated.

Cronstedt in his Mineralogy, published in 1758 definitely recognizes the mineral, terming it "Pyrites cupri hepaticus" according to a quotation in the later Latin edition of Wallerius. In the English translation by Engestrom[1] in 1770, bornite is classified in a subdivision of the main group of copper-minerals, headed "With sulphurated iron, minera cupri pyritacea," and is described as follows:- "Reddish yellow, or liver brown, with a blue coat on the surface, Minera cupri lazurea. This ore yields between 40 and 50 % of copper, and is commonly said to be blue, though it is as red when fresh broke, as a rich copper regulus."

The term"liver-ore" was probably the earliest name in common use in England. It is given by Forster in his "Introduction to Mineralogy,[2] published in 1768. He writes, "Liver-ore is a rich copper-ore consisting of a good deal of copper mixed with iron, of a yellow brownish colour, but mixed with some green spots, which distinguish them from the iron ores." The value of the mineral as an ore of copper was undoubtedly well known at this time.

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1. Axel Fredrik Cronstedt. An Essay towards a System of Mineralogy. Translated from the original Swedish, with notes, by Gustaf Engestrom. London, 1770, page 193. (Original published in 1758; translated into German in 1760.)

2. John Reinhold Forster. An Introduction to Mineralogy, or an Accurate Classification of Fossils and Minerals, viz., Earths, Stones, Salts, Inflammable and Metallic Substances. London 1768; page 46.

The gradual assembling of knowledge concerning bornite is easily traced in the increasing numbers of Mineralogies published. Richard Kirwan, who first approached the problems of mineralogical determination from the chemical side states in his Elements of Mineralogy (London 1784)[1] that the species termed Azure Copper Ore, Kupfer lazur, or Kupfer Malm is "mineralized with sulphur and with iron. Its color consists in various shades of blue; it contains 40 - 60% of copper, 20 - 30% of iron, and the remainder sulphur; the poorer it is in iron, the richer in copper. It has been by many confounded with indurated mountain-blue." In an edition of 1810, he adds that the mineral "effervesces with nitrous acid importing to it a green colour; does not immediately give a blue tinge to caustic volalkali. Its specific gravity is 4.956 - 4.983 and effervescence with acids prevents all possibility of mistaking it for the tarnished ores of the former family (copper pyrites)."

The first distinct analytical results to be published, appeared in 1797 and were the work of the mineralogist Klaproth.[2] Material from Hitterdahl in Norway and from the Friederike Juliane Mine in Rudelstadt, Silesia, yielded the following results:-

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1. Richard Kirwan, Elements of Mineralogy - London, 1784.

2. Martin Heinrich Klaproth, Beitrage zur Chemischen Kenntniss der Mineralkörper, Vol. II , p. 281, (1797).

	Hitterdahl	Rudelstadt
Copper	69.50 %	58. %
Sulphur	19.	18
Iron	7.50	19
Oxygen	4. %	5. %

The low summation of the copper, iron and sulphur led Klaproth to the conclusion that the variegated colors of the mineral were due to oxygen, which was believed to be present in sufficient quantity to account for the observed discrepancy. The persistance of the deep color of the bornite was believed to be due to the thorough absorbtion of oxygen, similar to but more intensive than the manner in which the action of air commonly produces an iridescent tarnish on chalcopyrite. For such early work, the results are remarkably close to the usual values of modern analyses especially if the "oxygen" is added to the sulphur percentages. The work is of distinct historical interest for it marks the beginning of a long and varied series of analyses and their accompanying controversies.

The name Buntkupfererz, which is commonly used in Germany to-day, was given the mineral by Werner according to statements in the books of several of his followers.[1]

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1. Emmerling, Mineralogy, 1796; R. Jameson, Mineralogy, 1805, and others. Hintze states eroneously that the name Buntkupfererz was given by Hoffman, (Min. 1816,36,110).

The term Buntkupfererz was translated into English as variegated Copper Ore, by Jameson[1] who gave a full description of the properties of the mineral in his Mineralogy published in 1805. He stated that it was found in beds, veins, and disseminated in rocks of different formations, and concluded that it occurred in greatest quantity in primative mineral beds, according to the Wernerian hypothesis of the formation of the rocks of the earth's crust. He regarded the mineral as an intermediate species between copper-glance and copper pyrites, and believed that it occurred as abundantly as the former, but not in as great quantities as the latter.

Haüy[2] gave a description of bornite under the name Cuivre pyriteux hepatique, and stated that bornite was regarded by many distinguished mineralogists to have originated from chalcopyrite. The bright and varied colors often observed on the surface of the "cuivre pyriteux" were regarded as the first products of the change.

The name Phillipsite was given the mineral by Beudant[3] in 1832, in honor of the mineralogist and chemist M.R. Phillips, who had described crystal forms (cubes and octahedrons) and analysed some specimens from Ross Island

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1. Robert Jameson, System of Mineralogy, Edinburgh, 1803. Vol. II., page 189.

2. C. Haüy, Traite de Mineralogie, Paris,1801.

3. Beudant, Traite de Mineralogie, Paris,1832, Vol.II, page 411.

in Killarney, Ireland.[1] The name is the oldest of the modern terminology, but owing to the prior usage of phillipsite for a member of the zeolite group, it has not been retained for the sulphide. Glocker[2] in 1839 created the term poikilopyrite, (from πoικιλos variegated,) but even though it may justly claim priority over others of the modern type, it is rarely if ever encountered in the literature.

Dana[3] in the first edition of his mineralogy (1837) called the mineral "Pyrites erubescens", alluding to its liability to tarnish and to assume a reddish hue. In the edition of 1850, the name was shortened to erubesite, but the term was discarded in the later editions, due to the earlier usage of the name bornite.

The commonly accepted name, bornite, was given the mineral by W. Haidinger[4] in 1845 in honor of Ignatius von Born (1742-1791). In a letter[5] to his father, Haidinger wrote; "The species was first definitely separated from chalco-

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1. Phillips, Mineralogy, 1819, page 222.

2. Glocker, Mineralogie, 1839, page 328.

3. J. D. Dana, System of Mineralogy, 1837, page 408.

4. W. Haidinger, Handbuch der bestimmenden Mineralogie, Wien, 1845, page 562.

5. Quoted in Hintze's Handbuch der Mineralogie, Bd. I, (1901), page 905 in a foot note.

cite and chalcopyrite in the classification of the Royal Mineral collection, which is being newly arranged under the direction of von Born." The claim that this was the earliest recognition of the distinct character of the species may be questioned, but by general usage the name bornite has been firmly established.

Polished surfaces of bornite were first made by H. Baumhauer[1] in 1885, to study the properties and relations of the mineral in some specimens from Chloride, New Mexico. He observed that the grain of the material was revealed by etching with nitric acid.

Products believed to be bornite have been obtainedartificially by various workers, but as the homogeneity of their material was established only in a rough way, the results have little more than historic value. One of the earliest experiments was by Bocking[2] in 1855. 36 g. of copper, 10 g. of iron (reduced from the oxide by hydrogen) and an excess of sulphur were melted together under a cover of salt, and a brittle regulus was obtained, which appeared like bornite on the fractured surface, and tarnished in moist air in a similar way. By analysis it contained: Copper 55.77., iron 15.9%, sulphur 25.9%

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1. H. Baumhauer, Ueber die mikroskopishe Beschaffenheit eines Buntkupfererzes von Chloride, New Mexico. Zeitschr. für Kryst., etc. Vol. 10, 1885, page 447.

2. Inaug. Diss. Göttingen,1855, 29. Hintze, Handbuch der Mineralogie, Bd. I.

Marigny[1] in 1864 obtained a crystalline aggregate of material resembling bornite by melting 29 parts of pyrite; 45 parts of copper shavings, and 20 parts of sulphur under a cover of borax.

Doelter[2] produced an aggregate of small cubes corresponding to the formula $Cu_3 Fe S_3$ by passing hydrogen sulphide over a mixture of $Cu_2 O$, Cu O and Fe_2O_3 at a low temperature. (100-200 C) without melting the oxides. The material agreed with natural bornite in color, specific gravity, analysis, and crystal form. With a mixture richer in copper, some covellite was obtained with the bornite.

Reuss[3] observed bornite and chalcopyrite irregularly intergrown in a black slag at Hermannseifen near Trautenan in Bohemia.

In the hot springs of Bourbon l'Archambault in the Département Allier, roman coins were observed altered to bornite and chalcopyrite; at Bourbonne-les-Bains in the Département Haute - Marne, small crystals of bornite were found on old coins in an artificial water course.[4] The forms (100)

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1. Marigny, Compt. rend., 1864, 58, 967. Hintze, ibid.

2. C. Doelter, Ueber d. kunstl. Darstell. einiger Mineral. a.d. gruppe d. Sulphide. u. Sulphosalze, Zeit. f. Krist. u. Mineral., Vol. 11, (1885-86), pp 36-38.

3. Lotos, Marz 1860, 10, 40. Hintze, ibid.

4. Daubree, Compt. rend., 1875, 80, 461, 604; and 81, 182, 834, 1008. Lacroix, Min. de France, 1897, 2, 677. Hintze, ibid.

Physical Properties.

Crystal forms. Bornite crystallizes in the isometric system. Good crystals are rare, but descriptions of material from many widely separated localities have established its forms with fair certainty. The cube and octahedron, alone or in combination, and the trapezohedron are the forms most commonly described. Dana notes the following forms and combinations:- (100) (110); (111) (110) (100); and (111) (110) (211). E. H. Kraus and J. P. Goldsberry[1] observed the following additional forms in material from Bristol, Conn.:- (211), (322), (433), (411), (522), (533), (833). Only 411 is considered doubtful.

Crystals of bornite several centimeters in diameter have been found in the Tyrol. The descriptions of the deposits in which they occur are very brief, but they are probably of the Alpine type[2]. Weinschenk describes crystals 3 1/2 cm. in diameter, on which the form (211) dominates with (100) less prominent. G. Gasser obtained crystals from the Frossnitzeralpe which measured 5.6 X 4.2 X 3 cm. Scalenohedrons of calcite and nodular particles of native gold, about 2 mm. in diameter, adhered to one side. The crystal forms (211) and (322) were observed. In the Hofmuseum in Vienna, there is a

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1. The Chemical Composition of bornite and its relation to other sulpho-minerals, A.J.S., Vol. 37, p. 539. (1914).

2. G. Gasser, Die Mineralien Tirols, einschliesslich Vorarlbergs und der Hohen Tauern, Innsbruck, 1913, p. 112.

specimen of bornite from the same locality which is a regularly formed trapezohedron about 4.3 cm in diameter. Its measurements yielded a new form for bornite, viz: (553). With it is associated native gold, calcite, and albite.

Other physical properties. Bornite possesses an octahedral cleavage.[1] The cleavage is rarely seen in the hand specimen, however, but may be easily developed on a microscopic scale by pressure with a blunt point. In the plane of the polished surface, series of straight cracks, usually parallel to two or three directions, or less commonly to four directions, which form in the bornite around the edges of crushed areas resulting from this pressure are undoubtedly due to the octahedral cleavage of the mineral. (fig.) The fracture on a coarse scale is uneven, but under the microscope it may be seen to be finely conchoidal. Bornite varies notably in brittleness. Material from certain localities breaks so readily that it is difficult to polish, while that from other deposits may be almost ductile. The hardness of bornite is 3. According to A. Sella, the specific heat is 0.1177 (calculated 0.1195)[2]. It is a good conductor of electricity; the resistance increases with the temperature.[3]

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1. Breithaupt, Berg and Hüttenm. ztg., 1859, 18, 322. Hintze, Loc. cit.

2. Beitrag. zur. Kenntniss der sp. Wärme der Min., Nach d.k. Ges. d. Wiss. zu Göttingen, 1891, 10, 211-322; also Zeit. f. Kryst. u. min., 22, 180.

3. Beijerinck, N. Jahrb., 1897, Beil. Bd., 11, 437; Hintze, ibid.

Bornite occupies a place below marcasite, chalcopyrite, enargite, covellite, and pyrite, and above galena, chalcocite, hematite, cuprite, metallic copper, and sphalerite in the electro-chemical series of the sulphides and oxides determined by V. H. Gottschalk and H. A. Buehler.[1] Measured against copper wire in distilled water, bornite was found by them to assume a charge of 0.17 volts.

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1. Oxidation of Sulphides (Second Paper), Econ. Geol., Vol. 7, p. 31. (1912).

Chemical Properties.[1]

Before the blow-pipe on charcoal in the reducing flame, bornite melts to a little magnetic bead with a gray-red fracture; with soda to a copper bead. In the open tube, sulphurous fumes but no sublimate are given off; in a closed tube, a weak sublimate of sulphur. Bornite dissolves with effervescence in nitric acid,[2] dilute or concentrated with the separation of sulphur. It is soluble in potassium cyanide solution,[3] whereby it may be separated from pyrite, chalcopyrite, magnetite and löllingite. It precipitates silver, often in crystals, from cool acid silver sulphate solution.

On the polished surface, nitric acid changes the normal pinkish brown color of the mineral to a golden yellow. It reacts with effervescence, leaving a surface etched in fine lines. Etching with potassium cyanide produces a brown surface, with an etch-pattern similar to that produced by nitric acid. Dilute reagents produce coarser etch-patterns than concentrated solutions. With both potassium cyanide and nitric acid, the surface between the cracks tends to arch. Frequently little pits are formed by the blocks springing out. (Fig. 115). The change is probably due to tension. Some specimens of bornite show it to a much greater degree than others. Boiling ferric chloride solution (5%) etches the polished

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1. Summarized in part from Dana's Mineralogy and Hintze's Hand. d. Min.

2. Richard Kirwan, Loc. cit.

3. Lemberg, Zeitschr. d. geol. Ges., 1900, 52, 489.

surface even better than the reagents mentioned.[1]

The etch-patterns produced by the action of both nitric acid and potassium cyanide on the polished surface of a bornite grain most commonly consist of one set of persistent and closely spaced cracks with the surface between them broken into imperfect brick-like blocks by short cracks roughly at right angles. (Fig.157). In certain orientations instead of the one strong and one weaker direction, three sets of feeble cracks develop which yield a pattern of short closely-spaced lines breaking the field into small rhombs or triangles. When three sets of short cracks form, they are parallel to the cleavage directions of the bornite; where one strong direction of the etch pattern is dominant, the cracks are usually not parallel to the cleavage directions.

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1. Joseph Murdoch, The Microscopical Determination of the Opaque Minerals, Wiley and Sons, New York, 1916, p. 65.

The Composition of Bornite.

The use of the metallographic microscope in the study of sulphide ores in recent years has made it apparent that pure bornite in sufficient quantities for analytical purposes is extremely rare. Material, apparently homogeneous when examined only with the hand lens, is often found to contain surprisingly large quantities of chalcocite, chalcopyrite or other impurities when the polished surface is studied microscopically. Crystalline bornite is usually found to be as impure as massive bornite, and is more deceiving, for the replacing sulphides are frequently concealed in the heart or basal portions of the crystals.[1] Consequently it is not surprising that there is little agreement among the analyses by the earlier mineralogists, who accepted the good crystalline form of the mineral as the sign of its homogeneity.

The earliest attempts to determine the composition of bornite were in 1784 by Kirwan and 1797 by Klaproth. Their results, which are of historical value only, have been mentioned on preceding pages. The formula $Cu_3 Fe S_3$, which is given in most text-books, was deduced by Plattner[2] in 1839 from an analysis of crystalline bornite from Cornwall. This was followed in the same year by an analysis of another Cornish specimen by Varrentrap[3], while a third by Chodney[4], appeared in the same journal in 1834. Subsequent studies have confirmed their analytical results in a rough way, but have shown that similar material from Cornwall is extremely impure, usually with chalcopyrite.[5]

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1. Joseph Murdoch, Op. cit., Page 36 and Frontispiece, Fig. 1.
2. Plattner, Pogg. Ann, 47, 351, 1839.
3. Varrentrap, ibid., p. 372.
4. Chodney, ibid., 1834.

The Composition of Society

The analyses are as follows:—

	I	II	III	IV	V	VI
Cu	56.76	58.20	57.89	57.71	57.68	55.58
Fe	14.84	14.85	14.94	13.89	15.11	16.36
S	28.24	26.98	26.84	27.17	26.46	28.06
	99.84	100.02	99.67	98.77	99.25	100.00

I. Condona Mine, Cornwall. Plattner.
II. Cornwall. Varrentrap.
III. Redruth, Cornwall. Chodney.
IV. &V. Cornwall. Harrington.(Bornite containing chalcopyrite, visible with a hand lens).
VI. Calculated for $Cu_3 Fe S_3$.

As Harrington points out the combination of

$Cu_5 Fe S_3$ and
$Cu Fe S_2$ yields
$2Cu_3 Fe S_3$, which is a mixture containing 73.2% bornite and only 26.8% chalcopyrite, assuming the first formula to be correct for bornite.

In 1875 Cleve recognized that few published analyses of bornite agreed with the formula $Cu_3 Fe S_3$. Results of several analyses done under his direction led to the formula $Cu_5 Fe S_4$, but from others more complicated formulae were derived which forced him to the conclusion that there were several forms of the mineral .

The various speculations of the following years are of little value, as the analytical evidence on which they were based is questionable. A long list of analyses is given in Hintze's Handbook für Mineralogie.[1]

In 1903, B. S. Harrington[2] published a series of analyses of bornite from various Canadian localities, and found that his results agreed closely with the formula $Cu_5 Fe S_4$. The uniformity of his results indicates that the material was carefully selected, but it was examined only with the hand lens, which can hardly be depended upon in general. His results are as follows:--

	I	II	III	IV	V	VI
Cu	63.55	62.78	62.73	63.34	63.18	63.27
Fe	10.92	11.28	11.05	10.83	11.28	11.18
S	25.63	25.39	25.79	25.54	24.88	25.55
Insoluble	---	.30	---	.38	.24	---
	100.10	99.75	99.57	100.09	99.58	100.00
S.G. at 15° C	5.085	5.055	5.090	5.029	---	---

I. Harvey Hill, P. Q.

II. Prince Mine, Ontario.

III. Dean Channel, Howe Sound, B. C.

IV. Copper Mt., Similkameen District, B. C.

V. Texada Island, B. C.

VI. Calculated for $Cu_5 Fe S_4$, for comparison.

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1. pp. 914-916.
2. Loc. cit.

Crystallized bornite, (partly massive, partly in rhombic dodecahedrons) from Bristol, Conn. was analyzed as follows:—

Cu	63.24
Fe	11.20
S	25.54
	99.98

Harrington concludes very justly from these data that the composition of bornite is correctly expressed by the formula Cu_5 Fe S_4, and that the divergence of analyses in the past was due to the impure nature of the material.

The question however was reopened by E. H. Kraus and J. P. Goldsberry in 1914. Two analyses were made of crystalline bornite from Bristol, which are as follows:--

			Average
Cu	65.42	65.91	65.665
Fe	9.74	9.67	9.705
S	24.79	24.51	24.656
	99.95	100.09	100.020

S.G. at ordinary temperatures 5.086

Their two analyses yield the formula Cu_{12} Fe_2 S_9. Pieces of the same material from Bristol as was analyzed by Harrington were obtained and his results checked. Based on this evidence, and numerous diverging analyses culled from the literature, the authors construct an elaborate series of minerals with the general formula Cu_x Fe_2 S_y, where

$y = X/2 + 3$. The series ranges from $Cu\ Fe\ S_2$ (chalcopyrite) through $Cu_{76}\ Fe_2\ S_{41}$ with chalcocite as the final limit. Each member differs from the preceding by the radical $Cu_2\ S$.

The bornite analyzed was examined by ordinary methods and considered pure. A metallographic examination of the material actually analyzed was not made, but material from the same group of crystals was studied in this way later and found to be pure. Similar specimens from Bristol, however, have been found to contain large amounts of chalcocite, consequently their high copper values are not above suspicion.

This morphotropic series postulated by Kraus and Goldsberry has been criticized by A. F. Rogers[1], who suggests that the variation in composition of bornite may be explained as the result of solid solutions of chalcocite in bornite of the formula $Cu_3\ Fe\ S_3$. The two analyses of Kraus and Goldsberry are accepted, but no new evidence is brought forward except a triangular diagram upon which numerous analyses given in Hintze are plotted. The dots form an irregular oval, the longer axis of which is roughly parallel to the line $Cu_x\ Fe\ S(\frac{x}{2}+3)$, but the coincidence is not striking. The most significant point brought out by the diagram is the clustering of dots around the point corresponding to the formula $Cu_5\ Fe\ S_4$. The obvious significance of the fact is disregarded by Rogers, who merely states that it may be explained as the value for the average solubility of chalcocite in bornite.

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1. Science, New Series, Vol. 42, p. 386, 1915.

E. T. Wherry[1] in a discussion of Rogers' paper differs from this interpretation, and shows that the variation in the composition of bornite may be explained equally well by assuming $Cu_5 Fe S_4$ as the formula of "normal" bornite, with the variation in one direction caused by the presence of chalcopyrite or pyrite in solid solution, and in the other direction by the presence of chalcocite. He does not favor the idea of solid solutions, however, but believes that the variations in apparently pure material are due to submicroscopic inclusions of chalcopyrite, pyrite or chalcocite. The limit of microscopic visibility (about 0.001 mm.) is determined by the wave length of light, and there is no reason to assume that the size of inclusions stops at this point. The suggestion is a valuable one for there is evidence which will be presented later, that submicroscopic chalcopyrite may develop in bornite. Even in such cases, however, the impure nature of the bornite is revealed by the abnormal color on the polished surface, and it is very probable that the variations in the analyses previously mentioned have been largely due to included material which could have been easily detected under the microscope. It is very improbable that submicroscopic pyrite is of importance. The difference in hardness of bornite and pyrite make even small grains of the latter very apparent when a bornite specimen is polished.

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1. Science, Vol. 42, N. S., p. 570, 1915.

The controversy over the composition of bornite, however, may be regarded as settled by analyses of the mineral in the Geophysical Laboratory in Washington, by Dr. E. T. Allen.[1] Polished surfaces of the specimens were carefully studied in all cases, and the material found to be practically free from impurities, with the exception of one specimen from North Carolina which contained a little chalcocite. Applying a correction in this one case, the results are remarkable uniform, and confirm Harrington's analyses closely. The formula $Cu_5 Fe S_4$ is indicated with a high degree of certainty. Dr. Allen's analyses are given below.

Analyses of Natural Bornites[2]

Locality	Superior, Arizona	Unknown	Costa Rica	Bristol, Conn.	Guilford Co., N.C.	Messina Transvaal	Cal. for Cu_5FeS_4
Cu	62.99	63.19	63.08	63.26	63.90	62.24	63.33
Fe	11.23	11.31	11.22	-----	10.79	11.12	11.12
S	25.58	25.44	25.54	-----	25.17	25.54	25.55
Pb	.10	none	none	-----	none		
Ag	none	.02	none	-----	none	-----	-----
	99.90	99.96	99.84		99.86	99.90	100.00
Mineral at 25° / Water at 25°	5.076	5.076	5.052	5.079	5.103	5.094	
Mineral at 25° C. / Water at 40°	5.061	5.061	5.037	5.064	-----	5.079	

1. Composition of natural bornite, A. J. S., Vol. 41, 1916, Pp. 409-413.
2. E. T. Allen, Loc. cit., p. 411.

Dr. Allen's paper concludes as follows:—

For the sake of completeness, we may include here a recent analysis of the bornite from Virgilina, Virginia, by Chase Palmer.[1] Palmer's material was examined metallographically and it is noteworthy that the principal impurity was

	Found	Cal. for $Cu_5 Fe S_4$
Cu	62.50	63.33
Fe	11.64	11.12
S	25.40	25.55
	99.54	100.00

chalcopyrite. Though the results are in fair agreement with $Cu_5 Fe S_4$, 'the relatively high proportion of iron suggests the presence of a small quantity of chalcopyrite which in preparing the sample for study has escaped detection.'

"Finally, observations of two physical properties of bornite confirm the chemical evidence. Murdoch[2] states that 'the mineralographic examination of polished surfaces of bornite from at least 30 different localities has revealed only an exceedingly slight variation in color and practically none in microchemical behavior. While reliance on density alone as a criterion of purity is unsafe, the determinations in the table [p. 38] are confirmatory. All the determinations are in good accord (5.061 to 5.079) except that on the Costa Rica specimen; and while it may be possible that we have here

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1. J. Wash. Acad. Sci., 5, 351, 1915.
2. Loc. cit., p. 35.

another crystalline form of the same composition; the low value for this bornite is reasonably accounted for by Dr. Merwin's observations, viz., that under the microscope it has a porous appearance.

"Aside, then, from these slight variations in composition which are so common throughout the mineral kingdom, and which are due to foreign admixtures or to solid solution, there is, in my opinion, no satisfactory evidence that natural bornite is variable in composition, or that it is even of any other composition than that expressed by the formula $Cu_5 Fe S_4$."

Still later investigations now about ready for publication by the chemists of the Geophysical Laboratory, show that synthetic products of the composition $Cu_5 Fe S_4$ agree in all respects with natural bornite whereas synthetic products of other compositions differ more or less notably from natural bornite.

PART III

DESCRIPTIONS OF DEPOSITS

PART III

DESCRIPTIONS OF DEPOSITS

MAGMATIC-PNEUMATOLYTIC DEPOSITS

Ookiep, Little Namaqualand, South Africa

The chalcopyrite and bornite deposits in the vicinity of the town of Ookiep in Little Namaqualand, Cape Colony, South Africa have been considered by many writers to be of magmatic origin.

This interpretation is supported by C. P. Tolman, Jr. and A. F. Rogers[1] who have recently published the results

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1. A study of the Magmatic Sulfid Ores, Leland Stanford Junior University Publications, University Series, 1916, pp. 59-60.

The following bibliography is given in Tolman and Rogers' paper:

Delesse, M. -- Sur les mines de cuivre du Cap de Bonne Esperance, Ann. des Mines, 5me. serie, 8, pp. 186-212, (1855).

Wiley, A. -- Report on the mineral and geological structure of South Namaqualand, Parliamentary Report, Cape Town, No. 36, p. 30, (1857).

Zerrener, C. -- Reise des Ingenieurs A. Thiers nach den Kupfer Bergwerken Namaqualande in Sud Africa, Berg. und Hüttenm. Zeitung, 1860, pp. 41-44 and 53-54.

Knopf, A. -- Über die Kupfererzlagerstatten von Klein Namaqualand and Demaraland, Neues Jahrh. f. Min. Geol. u. Pal., 1861, pp. 513-550.

Schenk, A. -- Die Kupfererzlagerstatten von Ookiep in Klein Namaqualand, Zeit. der deutsch. Geol. Ges. Verhand. der Ges., pp. 53, 64-65, (1902).

Kuntz, J. -- Copper ore in Southwest Africa, Trans. Geol. Soc. South Africa, 7, pp. 70-76 (1904).

-- Kupfererzvorkommen in Sudwestafrika, Zeit. f. prakt. Geol., 12, pp. 199-202, (1904).

Ronaldson, J. H. -- Notes on the copper deposits of Little Namaqualand, Trans. Geol. Soc. South Africa, 8, pp. 138-167, (1905).

Stutzer, O. -- Magmatische Ausscheidungen von Bornit, Zeit. f. prakt. Geol., 15, p.371, (1907).

Rogers, A. W. -- The nature of the copper deposits of Little Namaqualand, Proceed. Geol. Soc. Southwest Africa, 1916, pp. 21-34.

of a microscopical study of a suite of specimens from the district.

Specimens from this district have not been available for study in connection with this work, but as descriptions indicate that the magmatic origin of the ores is more definitely shown than in the case of any of the bornite deposits of this continent a brief summary of their important features will be given.

The ore-minerals occur in a great variety of coarse grained basic intrusives, among which norite, mica diorite, augite diorite, diorite, hypersthenite and anorthosite have been described. The rocks may be uniform within a single body, or two or more varieties may be associated. The contacts in these cases, however, are sharp, and interpreted as evidence of differentiation before intrusion. Dikes and sills are the commonest forms, but horizontal sheets, stocks, pipes and irregular branching bodies have been described and according to A. W. Rogers 344 of them have been mapped. (1916). The ore occurs in lenticular shoots, usually with the greatest dimension in a horizontal position. The ore-bodies occur in various parts of the intrusives and in some cases break into the wall-rock, which is the fundamental gneiss of South Africa.

The ore-minerals are magnetite, ilmenite, hematite, pyrrhotite, bornite and chalcopyrite. From the microscopical studies of Tolman and Rogers, it is established that the sul-

phides are without question later than the rock silicates. A small amount of euhedral magnetite occurs in the earlier rock minerals, but it is believed by the authors to be of replacement origin. The feldspars appear to be more easily replaced than the pyroxene, and the ores are more closely associated with them. Biotite is very susceptible to the attack of the sulphides, and is usually replaced by them along its cleavages.

The rocks from many of the mines show almost no traces of the alteration products which commonly accompany sulphide ores. Anthophyllite, clinozoisite and chlorite are mentioned, but are not of general occurrence. Anthophyllite, cutting bornite and chalcopyrite in a vein-like band, and penetrating the sulphides from the borders of grains, is described by Tolman and Rogers, and the relations are clearly illustrated by their excellent photographs.[1] Chlorite is said to be later than the sulphides. One of their photographs[2] shows a veinlet of chlorite breaking opaque minerals.

The sequence of the ore-minerals is not very clearly shown. From the shapes of grains, Tolman and Rogers state that it is probable that the bornite was formed in part by the replacement of magnetite. There is good evidence that chalcopyrite is later than pyrrhotite[3], and a suggestion

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1. Op. cit., Plate XIII, Fig. 55 and Plate XV, Fig. 62-63.
2. Ibid., Plate XVI, Fig. 65.
3. Tolman and Rogers, Op. cit., Plate XVI, Fig. 64.

that pyrrhotite has in part been formed by the replacement of magnetite.[1] The relation between the bornite and the chalcopyrite is not stated. Chalcopyrite gashes cutting the bornite are described, and are believed to be the products of post-magmatic readjustments.

The Ookiep ores for the most part are evidently of the same origin as many sulphide ores elsewhere which are commonly classified as magmatic. The ore-minerals are later than the original rock silicates, but this is commonly found to be the case in ores of this sort. Alteration products characteristic of hydrothermal ores are lacking or only slightly developed. The conditions under which the bornite in the Ookiep ores was produced may be regarded as more nearly magmatic than in the case of any other bornite deposit known. If the Ookiep ores are not strictly magmatic, they are at least the closest approach to magmatic bornite ores that have been described.

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1. Ibid., Plate XVI, Fig. 67.

La Fleur Mountain, Danville District, Ferry Co., Washington.

INTRODUCTION

Bornite ores of unusual interest are exposed in several prospects on the slopes of La Fleur Mt., Washington, a few miles south of the international boundary and about 10 miles southwest of the town of Grand Forks, B. C. The ores have not been described previously. The only information available concerning the general geologic relations is to be found in the reports of the Canadian Geological Survey[1], which deal with the Boundary District immediately to the north. The nearest mine, the Lone Star, a small property of the British Columbia Copper Company, is about 3 miles distant, and the large deposits of pyritic ore near Phoenix, worked by the Granby Co., are ten miles or more across the boundary. The mineralization of these deposits, however, is distinctly different in character from that of the bornite deposits, and there is probably no genetic relation between them.

The claims on La Fleur Mt. have been developed only to a very

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1. R. W. Brock, Summary reports of the Director of the Geological Survey of Canada for 1901 and 1902.
R. A. Daly, Geol. of the North American Cordillera at the 49th Parallel, Part I, p. 377, (1913).
O. E. LeRoy, The Geology of the Phoenix Mining District, Memoir 21, C.G.S., 1912.

Chapter Seventeen: Anatolia Revisited.
Part Six: Conclusions

Introductory

[illegible] vast of natural interest are exposed in several places on the slopes of Ik Dede [illegible], a few miles south of the intermittent swamp-lake of Tuz Gölü, S. W. The only lava not been described previously. The only interesting evidence concerning the recent eruption activities is to be found in the reports of the Canadian Geological Survey[1], which was sent with the Geological Expedition by the world. His account also, the lava flow, I would interpret by it the British Columbia Survey in about 1 mile distant, and the large deposits of pyrolis are made thereby, viewed by the Strait [illegible], are too alike at once across the mountain. The circumstances of these deposits, however, is distinctly different in character from that of the Anatolia deposits, and therefore entirely no genetic relation between them.

The claims as to clear ET. have been developed only in a very

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1. J. B. Dowling, Summary Reports of the Director of the Geological Survey of Canada for 1905, 1906 [illegible].
2. J. D. Hulse, Trans. of the Royal Geological Institution of the Arts Canadian, Part I, p. 277, [illegible].
3. C. J. Abney, The Geology of the Anatolia Lignite Deposits, Toronto, Ontario, 1912.

slight extent by a few shallow shafts or short adits. A little ore has been mined, and shipped, but no noteworthy work has been done.

GEOLOGICAL RELATIONS.

The older rocks of the mountain form a series of various sediments, of which limestone beds and some altered porphyries are prominent members. From the mapping on the Canadian side of the line, it is possible that the sedimentary rocks may be members of the Attwood series, argillites, quartzites and limestones, stated to be of Carboniferous (?) age. A diorite porphyry, now altered in places to a somewhat schistose rock containing abundant biotite and shreddy amphibole, is associated with the sediments, but neither its exact relations to them nor the form of its bodies could be detected. The original rock possessed small phenocrysts of andesine, oligoclase and biotite, set in a microgranitic ground mass of the same mineral, in which there is also a little orthoclase and fine shreds of amphibole.

The older rocks of the mountain are intruded by an irregular mass of gabbro. The rock varies from dark varieties, in which hornblende becomes prominent, to lighter types in which feldspar predominates. In the commonest form, the rock possesses a medium to fine grained texture, and is composed chiefly of acid labradorite ($Ab_5\ An_5$) and colorless to pale

green augite. Hornblende is usually present, apparently formed in part at the expense of the pyroxene. In places, the rock becomes of dioritic character. The mass of the rock is cut by numerous small seams of pegmatitic material, nearly always feldspathic, with little or no quartz. They are usually less than one inch in thickness.

The gabbro is cut by dikes of coarse syenite, averaging about four feet in width, but occasionally much wider. In places, the rock becomes distinctly pegmatitic in character, with the orthoclase in crystals two or three inches long. A sub-parallel orientation of the feldspar prisms is usually prominent. It suggests a flow structure. The chief mineral of the syenite or the syenite-pegmatite is orthoclase. Under the microscope, albite is found to be common also, usually in smaller grains around the margins of the coarser orthoclase, and to a slight extent in microperthitic intergrowths. Muscovite is the only other mineral prominent in the syenite. It occurs as medium grained flakes of slightly greenish tinge when seen with the unaided eye. The mica is closely associated with the albite, and is usually a constituent of the zone of finer grains surrounding the coarse orthoclase crystals. Both the albite and muscovite are in part later than the orthoclase. Other constituents are of little quantitative importance. Titanite in sharp crystals is not uncommon,

and there is a little apatite. Where in contact with the altered porphyries of the older series, a little augite sometimes developes in the dike rock. Other modifications with respect to the wall rocks are closely related to the processes of the mineralization and will be described in that connection. The dikes are in a north-south zone and may be traced about a mile, although no single dike is continuous for that distance.

The latest igneous rock is a gray diorite porphyry, which forms a broad dike cutting all other formations. It is fresh and unmineralized, and in striking contrast to the older and more or less altered rocks of the mountain.

MINERALIZATION

Ores in the Syenite Dikes. The mineralization is closely associated with the syenite or syenite-pegmatite dikes. The sulphides, bornite and chalcopyrite, are most abundant in the dikes themselves, but where the dikes cut the gabbro, the sulphides penetrate the wall-rock along fine seams or occur disseminated through it to a slight extent. The mineralization in the dikes however is not continuous and it is only locally that the sulphides are sufficiently abundant to constitute an ore.

The ore-minerals corrode the orthoclase, albite and muscovite, but with the exception of an albite rim which

often is present between the ore-minerals and the orthoclase, there is no other important alteration of the rock-minerals. A little fine-grained muscovite or sericite is sometimes developed in the albite, and later calcite replaces the feldspars to a slight degree, but the absence of alteration products which usually accompany sulphide mineralization is an outstanding feature.

Mineralization in the Wall-rocks. Where the dikes cut the limestone members of the sedimentary series, a garnet rock is formed composed chiefly of andradite, albite and calcite, with a little diopside, titanite and apatite. The rock contains numerous small cavities between the crystals of its constituents, and a scattering of chalcopyrite grains. Garnet is also abundant in one part of the syenite dike on one of the claims on the east end of the mountain, and is probably to be attributed to the influence of limestone on the magma. The garnet is poikilitic with albite, and probably crystallized later than the feldspars. The mica in this part of the dike is biotite (deep green parallel to c , pale yellowish green to colorless perpendicular to c), and the colorless muscovite, abundant elsewhere, is in small flakes and quite subordinate.

Where the mineralization has penetrated the gabbro, there is more pronounced rock-alteration. There is a notable increase in hornblende near the dikes, and also along the small

seams of feldspathic pegmatitic material which cut the rock. The sequence of minerals is well shown in one thin section which includes a portion of the edge of one of these stringers. The pegmatitic material is largely orthoclase and albite, in microperthitic relations for the most part; near the margins garnet is slightly developed. In the rock nearest the seam, hornblende is most abundant. In places it possesses a rim of deeper green than the heart of the grain; (pleocroism: deep green parallel to b; yellow or pale brown parallel to a; light yellow or yellowish green parallel to c). Farther into the rock, pyroxene (colorless augite) becomes of greater importance and is the chief femic constituent. Epidote and chlorite are abundant in the rock, as replacements of hornblende, pyroxene and the feldspars. The older plagioclase of the rock contains abundant sericite and calcite. Apatite and titanite are somewhat more abundant in the rock than is usually the case. The chief opaque mineral in this particular slide is magnetite, which is later than the pyroxene and feldspars, and in part at least, later than the hornblende, for all the preceding minerals are clearly corroded by it. It frequently includes small apatite grains.

Ore-Minerals. The ore-minerals are chiefly chalcopyrite and bornite. The former is slightly more abundant. Magnetite is largely confined to the gabbro; it was not observed in ores from the syenite. The ore-minerals in the dikes are later

than the rock-minerals, as has been stated, although probably not very much later, for there are so few alteration products associated with them. In the gabbro, they are probably contemporaneous with the epidote and chlorite.

The chalcopyrite and bornite are usually in close association, and in part probably of contemporaneous origin. The contacts between the two minerals, as shown on the polished surface, are smooth and even, with few irregularities such as tongues or veinlets which would definitely show sequence. In many cases, their relations to each other would be little altered if the two minerals were interchanged. This relation has been termed the mutual boundary[1], and is believed to be particularly characteristic between minerals of the primary sequence (figure 67). There is a little evidence, however, of corrosion of the chalcopyrite by the bornite in some places, and it is probable that conditions favoring the formation of bornite continued after the deposition of chalcopyrite had ceased, which resulted in a slight replacement of the chalcopyrite by the bornite. This interpretation is shown more clearly on the diagram of mineral sequence.

Magnetite, and a small amount of specularite are probably earlier than the sulphides, but their relations could not be determined with final satisfaction in this deposit.

A little sphalerite, galena, and tetrahedrite were ob-

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1. L. C. Graton and D. H. McLaughlin, Ore deposition and enrichment at Engels, California, Econ. Geol., Vol. XII, 1917, p 17.

served as small specks on the polished surfaces in the midst of the more abundant sulphides.

OXIDATION AND ENRICHMENT

The deposits occur in a mountainous region of mature topography (Fig. 6) and possess no noticable gossan, a fact which may be attributed to the present vigorous erosion and preceding glacial scour to which they have been subjected. A small amount of limonite and malachite occur, but the sulphides outcrop directly at the surface in a fairly fresh condition. A small amount of chalcocite, covellite and chalcopyrite occur in the bornite, and are undoubtedly to be attributed to the processes of secondary enrichment, but as far as their total copper content is concerned, they are of little importance.

The chalcocite is in fine veinlets or rims associated with the bornite. It follows the easy channel-ways afforded by the contacts of bornite and the gangue or rock minerals, or seeks out grain boundaries, seams or other obvious lines of attack. Covellite is for the most part the first stage of the alteration of chalcocite to malachite and usually occupies an intermediate position between the two minerals. It develops directly from bornite, however, to some extent. The veinlets of chalcocite and covellite penetrate the primary chalcopyrite, but the latter is clearly more resistant to alteration, and they do not develop as easily as in the bornite.

The bornite in the neighborhood of the chalcocite and covellite veinlets commonly contains a small amount of chal-

covered in small figures on the polished surfaces of the white
of the more abundant minerals.

copyrite, which is closely related in origin to the secondary sulphides. The chalcopyrite in this association developes as plates in the bornite, apparently oriented parallel to three or rarely four crystallographic directions, which on the polished surface yield the reticulate pattern known as the lattice structure. In some grains of bornite, the plates of secondary chalcopyrite are so thin and so finely spaced that they are scarcely visible under the highest available magnifications, and it is justifiable to assume that the peculiar yellow color of certain areas of bornite in the same vicinity is due to submicroscopic chalcopyrite of this sort.

DISCUSSION

The possibility that the syenite and syenite-pegmatite dikes are late products of the same magma which produced the gabbro offers a problem of great interest. The small seams of pegmatitic material which are common in the gabbro, and which would ordinarily be accepted as its pegmatitic phases, are closely related mineralogically to the syenite, and are probably of the same origin. The greater alteration and more abundant mineralization of the gabbro along the ore-bearing portions of the syenite dikes than is the case where other rocks are encountered might be interpreted as an indication that the gabbro was still heated at the time of the intru-

sion of the syenite, and in a receptive state to react with the vapors given off. There is no evidence against the view, and although the arguments in its favor are not of direct or compelling character, the suggestion that the syenite dikes and the ores are final products of the same magma from which the gabbro crystallized remains a rather attractive hypothesis.

The syenite contains numerous miarolitic cavities, which may be regarded as a strong indication that gases played an important rôle both in the formation of the differentiate and in the determination of the character of the crystallization. The abundance of hornblende in the gabbro near the edges of the dike also testifies to the importance of mineralizers. The concentration and formation of the various ore-bodies was very probably the work of the same agencies.

The ores are magmatic in the sense that they are associated in close relationship with the feldspar of the syenite dikes. The ore-minerals, however, are later than the rock minerals, and were probably formed either during the closing phases of the magmatic period or under pneumatolytic conditions. The abnormal character of the dikes (the variable texture, the coarse grain usually with the ores, and the abundant miarolitic cavities) indicates that the concentration both of the syenite and the ore was a pneumatolytic process. Consequently it seems nearer the truth to consider the ores to be of pneumatolytic rather than of direct magmatic origin. The

Diagram of Mineral Sequence.

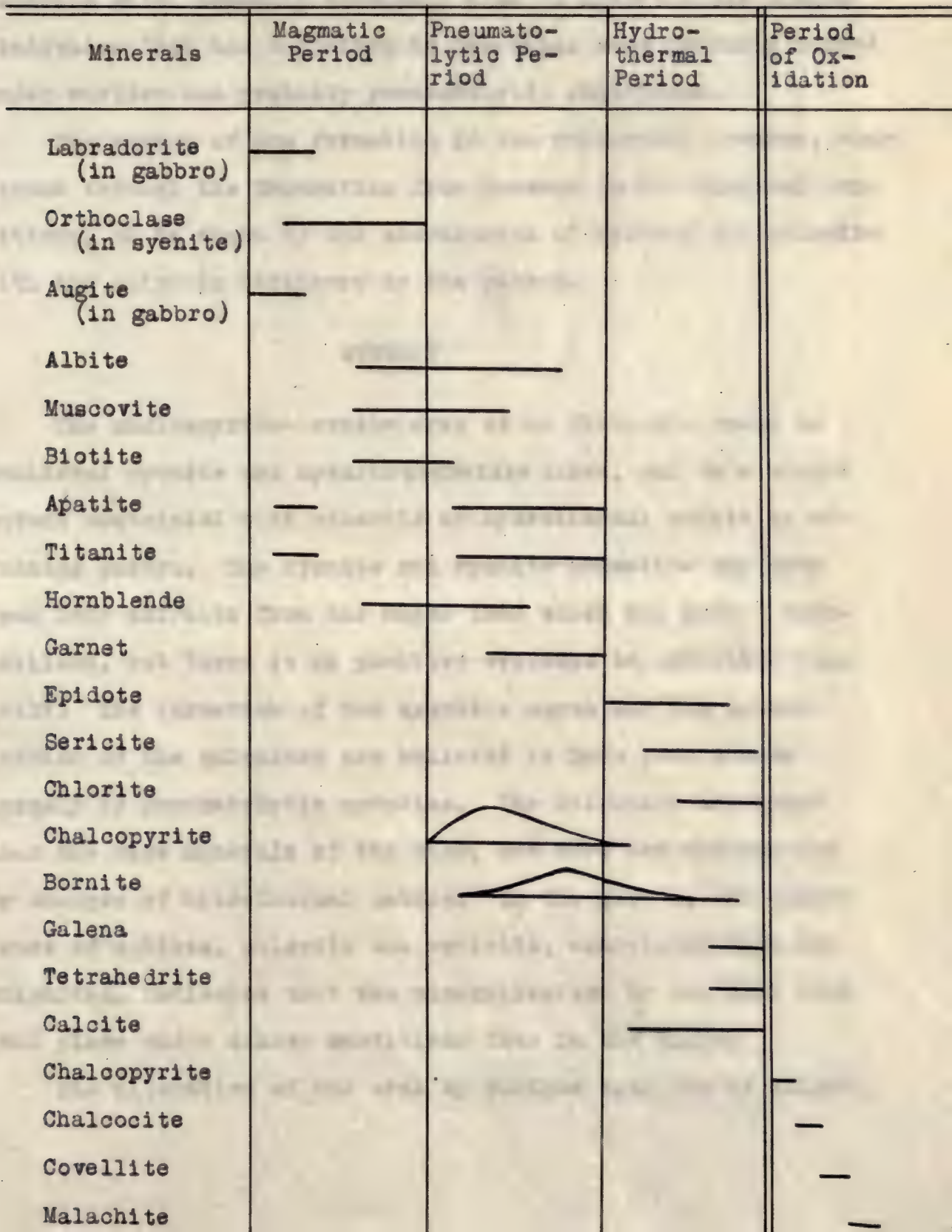

Diagram of Vertical Extension.

Minerals	Magmatic Period	Pneumatolytic Period	Hydrothermal Period	Period of Decomposition
Tourmaline				
Orthoclase (in gneiss)				
Quartz (in granite)				
Augite (in gneiss)				
Hornblende				
Mica				
Apatite				
Titanite				
Staurolite				
Garnet				
Epidote				
Cerussite				
Calcite				
Chrysoberyl				
Beryl				
Opal				
Tetradymite				
Cyanite				
Dimorphite				
Chiastolite				
Cassiterite				
Stibnite				

almost complete absence in the syenite of the usual alteration products which commonly accompany ores of hydrothermal origin indicates that the sulphides in the dikes were probably formed under earlier and probably pneumatolytic conditions.

The period of ore formation in the wall-rock, however, continued through the transition from gaseous to hydrothermal conditions, as is shown by the association of epidote and chlorite with the sulphide stringers in the gabbro.

SUMMARY

The chalcopyrite-bornite ores of La Fleur Mt. occur in unaltered syenite and syenite-pegmatite dikes, and to a slight extent associated with minerals of hydrothermal origin in adjoining gabbro. The syenite and syenite-pegmatite may have been late extracts from the magma from which the gabbro crystallized, but there is no positive evidence to establish this point. The formation of the syenitic magma and the concentration of the sulphides are believed to have been caused largely by pneumatolytic agencies. The sulphides are later than the rock minerals of the dike, but were not accompanied by changes of hydrothermal nature. In the gabbro, the occurrence of epidote, chlorite and sericite, associated with the sulphides, indicates that the mineralization in the wall rock took place under milder conditions than in the dikes.

The alteration of the ores by surface agencies is slight,

but affords a clear example of bornite altering to chalcocite and covellite with the development of secondary chalcopyrite in fine lattice structures in parts of the bornite protected from direct attack by the oxidizing agencies.

The Evergreen Mine, Gilpin Co., Colorado.

INTRODUCTION

The copper ores of the Evergreen Mine have attracted the attention of geologists during the last few years on account of the intimate association shown to exist there between the sulphides of copper and the apophyses of a neighboring stock of monzonite. The copper minerals, chiefly bornite and chalcopyrite, occur largely in two small igneous dikes, and in the matrix of an igneous breccia formed by the complex intrusion of the molten mass into the walls of shattered schist and pegmatite.

Situation. The little town of Apex, near which the Evergreen Mine is situated, is well in the heart of the Front Range of the Rocky Mountains, in the high region seven miles east of the Continental Divide. The nearest railway point is Central City, about 6 miles to the southeast, which is the terminus of a narrow gauge line of the Colorado and Southern Railway, which ascends the rugged cañons of Clear Creek and its northern tributary from the town of Golden. The topography is mapped on the Central City sheet of the U.S.G.S.

Development. The mine has been operated in a small way for nine or ten years. A shaft about 350 feet deep has been sunk, and levels run at 100', 200' and 330'

respectively. A little ore has also been mined from a tunnel penetrating the deposit from a point on the surface north of the shaft. A small mill has been erected recently, and at the time of my visit some experimental work with flotation methods was being done. Very little ore, however, has been shipped.

Literature. In the first published description of the deposit, a paper by E. A. Ritter[1], the opinion was expressed that the ores are primary constituents of the intrusive rock, and crystallized directly from the magma with the rock minerals. The unusual concentration of the sulphides is regardedas a segregation caused by sublimations from the magma. The ore-bearing intrusive is described as a rock composed "of quartz, alkali feldspars, orthoclase and albite, (often interlocked as microperthitic), with augite of the aegirine variety and long needles of enstatite and diallage", and the name Evergreenite is given it. Phases termed microgranitic and porphyritic are mentioned, the latter being regarded as a more advanced stage of the segregation as it is characterized by a greater abundance of enstatite and diallage, or of quartz. The mention of micropegmatite in the "microgranitic" phase is of interest, and the structure is well shown in a photograph of a thin section. Two types of alteration of the country rock (a biotite

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1. E. A. Ritter, The Evergreen Copper Deposit, Colorado, T.A.I.M.E., Vol. 38; pp. 751 - 765 , (1907).

schist) were observed by Mr. Ritter, viz.,

(1) an introduction of quartz and aegirite forming pseudo-schists, and

(2) the formation of pseudo-gneisses by the development of alkali feldspars and aegirite, the biotite remaining little altered.

Covellite is described as an alteration of bornite and chalcopyrite due to descending waters, but it is not common, and is believed to be confined to the ore adjacent to the schist and not in the massive intrusive.

Bastin and Hill in a later article[1] add new data concerning the mineralogy of the ore, and come to some interesting conclusions regarding its genesis. The colorless pyroxene in the intrusive is shown to be wollastonite, and not enstatite or diallage as determined by Ritter. The occurrence of garnet in the rock with the wollastonite is regarded as suggestive of the digestion of calcareous wall rock by the magma, probably before it reached its present position. The authors support Ritter's view that the sulphides are primary constituents of the dike rock, but they believe them to have been derived either from the wall rocks at depth by absorption or from the magma by differentiation. Their conclusion is:-- "The deposit under this view represents an endomorphic effect produced by contact metamorphism at the border of a large intrusion of monzonite."

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1. E. S. Bastin and J. M. Hill. The Evergreen Copper Mine, Colorado. Econ. Geol. Vol 6. pp. 465-472 (1911).

Physiographic Features. The Evergreen Mine is at an altitude of 9800, in a region of rather subdued relief, slightly above the line of the precipitous slopes of the deep cañons. If the great relief due to the youthful V-shaped gorges of the present master streams is ignored, the topography above the 8000 foot contour is rather subdued; the slopes are gentle, the ridges well rounded and in places flat-topped, and the valleys open and with frequent meadows. The highest peaks of the range rise 3000 or 4000 feet above this general surface, but with surprisingly gentle and regular slopes for such high altitudes. Glacial cirques interrupt the smoothness of their contours for the last thousand feet or more, but the glacial erosion is far from mature, and has failed to destroy the older surfaces completely. From the neighborhood of the mine, I saw few peaks which could not be ascended on horseback. The high surface of relatively gentle relief is sharply incised by the master streams of the region, and the cutting has worked back along the tributaries in varying degrees. Between Black Hawk and Golden, the North Fork and main stream of Clear Creek have cut a cañon 2000 feet deep, in places with high cliffs, and many of the smaller valleys of the same drainage basin present strikingly abrupt slopes, as is shown in the figures. The three distinct topographic features, which have been described above, may be summarized as follows:--

PLATE I.

The Evergreen Mine, Gilpin Co., Colorado.

Fig. 1. The Evergreen Mine from the south east.

Fig. 2. The Evergreen Mine and the valley of Pine Creek from the south.

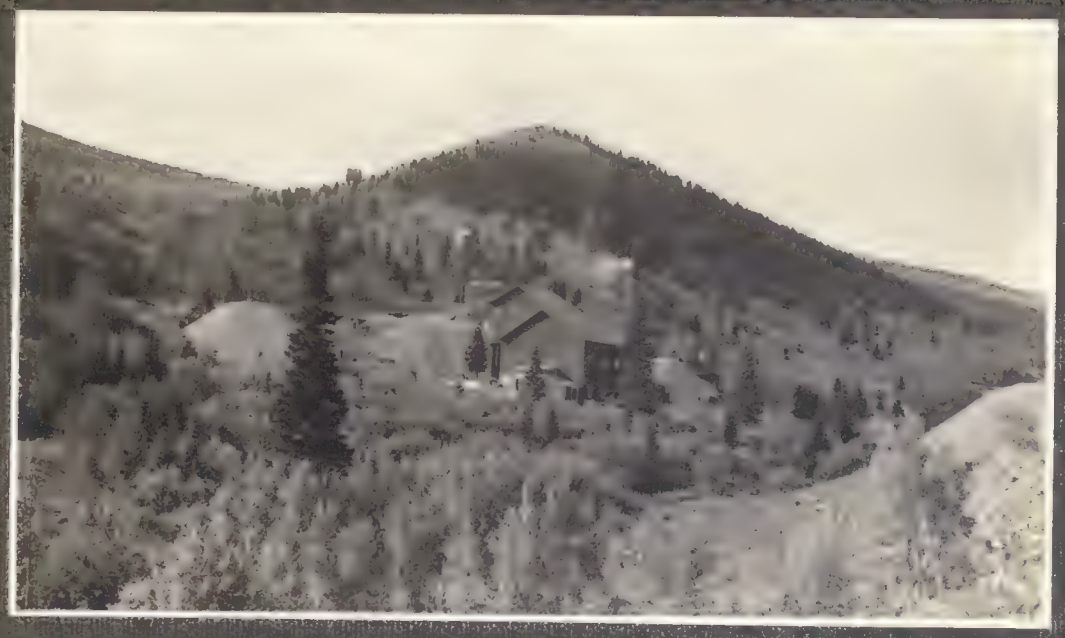

PLATE II.

The Region near the Evergreen Mine, Gilpin Co., Colorado.

Fig. 3. The valley of Clear Creek looking south east from a point 2 1 2 miles northwest of Central City.

Fig. 4. The valley of Pine Creek, looking south from a point near the Evergreen Mine.

(1) the old surface of moderate relief,

(2) the sharp V-shaped valleys dissecting it, and

(3) the glacial cirques modifying the slopes of the higher peaks.[1]

The Evergreen ore-body is in a shallow valley of the older cycle of erosion in the region of moderate topographic relief. It is still above the reach of the actively cutting youthful streams. The climate is severe, the snow lasting for seven months, but the under-ground workings are rarely below freezing.

General Geologic Features. The district is in the wide area of pre-Cambrian rocks, which form the greater part of the Front Range. The oldest formation is a fine-grained biotite schist, believed to be of sedimentary origin. Into it are intruded several plutonic rocks also of pre-Cambrian age, showing various degrees of metamorphism. Pegmatitic intrusions associated with the granites are very prominent, in places cleaving the fissile schists as broad dikes tens of feet in width, elsewhere forming numerous fine laminae in the earlier rock.

The only rocks younger than the pre-Cambrian are various early Tertiary intrusives, chiefly monzonitic in character, which form many small stocks and dikes. The longer axis of these later bodies is usually roughly parallel to the schistosity of the metamorphic rocks, although in some cases the intrusions are quite irregular. The

1. Spear and Garrey also recognize similar topographic features in the Georgetown Quadrangle. (Prof. Paper 63, U.S. G.S., The Geol. of the Georgetown Quadrangle, Colorado.)

chief ore-bodies of the region, the gold-silver veins and the tungsten veins, are clearly related to the Tertiary intrusives, and no claim is thoroughly satisfactory to the prospector which does not show an outcrop of porphyry.

DESCRIPTION OF THE DEPOSIT.

The occurrence of copper in workable amounts is rare in the district and the ore-body on the Evergreen Claim is the only one which supports a mine. The dependence of the ore on the dike rocks is unusually definitely shown, and the evidence read from the relations there, greatly strengthens the general belief that the "porphyries" were the mineralizing agents throughout the region.

Associated Rocks. The wall rock of the deposit is the pre-Cambrian biotite schist, with numerous tabular and lenticular intrusions of a siliceous pegmatite. Although none of the thin sections show the schist without some alteration due to the mineralizing fluids, the original rock may be readily inferred to be composed of fine flakes of a deep brown-green biotite (deep brownish-green parallel to c; pale green perpendicular to c), and a fine-grained aggregate of orthoclase and quartz. The pegmatitic material is chiefly quartz and orthoclase, in coarse irregular masses.

To the east of the mine, a stock of monzonite outcrops, and the two dikes with which the ore is associated, are very probably apophyses of this stock. The dikes strike

a little west of north, and dip steeply (60-70°) to the east, being approximately parallel both in strike and dip to the structure of the schist. The dikes are about twenty feet apart. The one to the east is the larger, averaging 13-15 feet thick, while the one to the west varies from a few inches to about three feet.

In places the wall rocks are penetrated irregularly by the intrusion of the igneous material, producing masses of igneous breccia often of notable extent. The rocks between the two dikes have suffered this brecciation particularly. Places were observed in which the identity of the dikes themselves becomes lost in a confused mass of this shattered schist. All gradations exist from the ratio of wall rock to intrusive in which the schist fragments are properly described as inclusions, to the conditions in which the wall rock predominates, and the igneous rock fills irregular fractures in it. The schist and pegmatite appear as if shattered by violent explosions, and then cemented by the intrusive rock. The fragments of the breccia vary from small chips, a fraction of an inch in thickness to blocks a couple of feet wide.

The normal dike rock is a fine-grained hypidiomorphic granular rock, of a medium gray color, with small feldspars and pyroxenes visible with the hand-lens. For the most part it is even-grained, but in places there is a sub-porphyritic development of the orthoclase. Under

the microscope, the unmineralized rock is seen to contain orthoclase as the chief constituent (in part microperthitic with albite) with somewhat less abundant quartz. A small amount of oligoclase is sometimes present. Green augite (non-pleocroic or only faintly pleocroic) is the most abundant dark mineral, but a little pale blue-green amphibole was observed in one slide, and a few laths of deep green biotite, (deep green parallel to c, light yellow green perpendicular to c). Titanite crystals and small prisms of apatite and zircon are common accessories. The orthoclase grains average about .5- .75 mm. in longest diameter, with a maximum of about 1.5 mm; the quartz usually about .5 mm, and the pyroxene .5 mm, with a maximum of 1 mm. From the microscopic work, the rock seems more nearly a granite in mineral composition than a monzonite.

Approaching the ore-bodies, the dike rock alters to a peculiar alkaline granite, with aegirite-augite, and fine laths of wollastonite usually in great abundance. In the hand-specimen, it is a light colored, fine-grained rock with a peculiar pearly luster, distinctly different from a normal feldapathic rock. In some cases, the laths of wollastonite are sub-parallel; in others they form an interlacing mass. Orthoclase with some microcline, quartz, wollastonite and the deep green aegirite-augite are the chief components of the rock. A little plagioclase (oligoclase -

albite?), good sphenes of titanite, and small crystals of zircon are accessory.. Apatite is abundant, in some cases as large grains. The aegirite-augite forms small stubby crystals, usually with a pale green, non-pleocroic core which is in striking contrast to the deep green tints of the outer portions of the grains. The extinction angles of both portions of the crystal are high, but differ by a few degrees, the outer portion having a slightly lower angle of extinction than the inner. The feldspars and quartz are in the usual hypidiomorphic relations, and of about the same grain as described for the normal rock. The wollastonite, which is the most unusual feature, is in long laths, (max. about .75 mm.), commonly in sub-parallel orientation. It is most ordinarily grouped along the contacts of grains, and tends to avoid the quartz, although a few prisms penetrating the latter were observed. It projects into the feldspars in some cases, but the relations may be explained equally well by assuming a replacement origin for it, as by assuming it to be a primary rock mineral. The parallel structure shown by the wollastonite is not shown by the other rock minerals except to a slight degree.

. Bastin and Hill mention finding abundant garnet in the dike-rock, and in the breccia, but in the thin sections of my specimens it is not an important mineral. The unusual abundance of apatite does not seem

to have been emphasized by the previous writers.

The dike rock containing the sulphides, and the rock forming the igneous breccia is the aegirite-augite and wollastonite bearing phase of the granite. For the most part, the thin western dike (the mein Evergreen dike) consists entirely of the wollastonite bearing rock, but on the 300' level, where a drift has been pushed several hundred feet to the northwest along it, it changes without any distinct boundary into the normal gray granite. In one place the change required about 10 feet, - in another it was apparent within the dimensions of a hand-specimen.

The wollastonite-bearing rock is probably the rock named "Evergreenite" by Ritter, but as it has been proved by later work[1], to be of different mineralogical composition and as it is merely a modification of an alkaline granite, it seems hardly worth while to burden the already bewildering list of rock types with another name. The name, however, serves the local needs admirably, and will be used to refer to the wollastonite bearing phase of the alkalian granite associated with the ores.

Primary Mineralization and Rock Alteration. The common ore-minerals are chalcopyrite and bornite, present in about equal amounts. The largest masses of the two sulphides occur in the "evergreenite", usually not in the dikes them-

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1. Bastin and Hill, Loc. cit.

selves but in the irregular intrusions in the brecciated wall rock. The inclusions of schist or pegmatite contain fine seams of chalcopyrite, or disseminated specks of chalcopyrite or bornite, but no large masses of the ore-minerals were observed except in the igneous matrix itself. The dike rock associated with the ore contains numerous miarolitic cavities, and in places develops a coarser structure, suggesting pegmatitic tendencies. The presence of micropegmatite in these rocks mentioned by Ritter is in accord with this observation. In the miarolitic cavities crystals of orthoclase, with crocidolite, and imperfectly crystallized grains of bornite and chalcopyrite between them, were observed in a few cases. Fluorite occurs in small grains in the intrusive, usually in the miarolitic portions. A few particles believed to be tourmaline were observed, but were not positively identified.

Hydrothermal minerals are not common, but epidote is associated with the bornite in many cases. It fringes the bornite grains, replaces the feldspars and pyroxenes, or cuts across the rock in veinlets.

Sericite is somewhat developed in the feldspars, but on the whole it is not very abundant. In one of two cases, laths included in the outer portions of bornite grains were observed, and interpreted to indicate the extension of the period of bornite formation into the period of conditions favorable for sericite (i.e. hydrothermal).

Calcite is common, replacing both the earlier rock minerals, and the wollastonite. The latter is particularly susceptible to the attack of the calcite, and in many specimens, its previous existence in the rock can be inferred only from the lath-like forms assumed by the calcite. The calcite seems a little later than the epidote, and is most probably a product of the closing phases of the emanations which formed the ores.

As seen in the field and in the hand-specimens, the schists present fairly sharp boundaries against the invading dike-rock, but in a few places, intimate injections along the cleavages of small fragments have reduced them to mere bands of the dark constituents (chiefly biotite) floating in coarser grained bands of the intrusive. Under the microscope, the schist is seen to contain in many cases, a blue-green amphibole in broad, rather irregular grains, up to .5 to .75 mm. in length, which commonly contains abundant inclusions of fine flakes of the biotite of the schist. (The microscopic properties fail to identify the amphibole with any of the ordinary varieties. They may be summarized as follows:-- Index and birefringence somewhat less than augite; amphibole cleavage; oblique extinction to c, max. angle 41°; pleocroic, light blue-green parallel to a; optically positive(?). Pale cores with more deeply colored rims are common. The change is accompanied by a slight increase in the angle of extinction). The longer

axis of the amphibole is usually parallel to the schistosity. Its similarity to the amphibole observed in the normal granite, and the inclusions of biotite favor the view that it is a product of emanations from the intrusive, reacting with the minerals of the schist.

The borders of the schist inclusions may be seen with the aid of the microscope to be usually lined with fine grains of deep green aegirite-augite. Fine grains of augite are abundant throughout the inclusions, but as they occur along veinlets in a few places, and seem closely related to the aegirite-augite near the margins, they were probably introduced from the magma. The augite grains do not occur as inclusions in the amphibole in the schist, and are probably later.

The feldspathic portions of the schist are partially recrystallized, especially near the edges of the inclusions. Large grains of orthoclase, surrounded by fine-grained aggregates of biotite and augite, although united in one fairly definite crystal, still show by their wavy extinction, the irregular interlocking boundaries of the grains from which they were welded. Irregular, elongated grains of dirty looking titanite are common, frequently associated with a peppery aggregate of small magnetite specks. Both minerals are probably original constituents, but they seem to have suffered many hardships in their severe experiences of successive intrusions.

The pegmatitic material is little altered by the dike-rock. The occurrence of coarse quartz in certain brecciated zones is rather puzzling to interpret, but it is most probably pre-Cambrian material for very siliceous phases of the pegmatites were observed. The coarser types of the ore-bearing rock become almost pegmatitic in small areas, but rarely approach the grain of the older material.

Epidote and sericite are developed to varying degrees in both types of the wall rock. The fine-grained feldspars of the schists are especially susceptible to the attack of the sericite, but they and the other minerals of the schists usually show less alteration to epidote than the minerals of the igneous matrix.

The bornite and chalcopyrite are present in approximately equal amounts. The contacts between the two minerals are commonly sharp and definite, with smooth unbroken lines, and as commonly showing blunt penetrations of the bornite by chalcopyrite, as of the chalcopyrite by the bornite; in brief the minerals exhibit mutual boundaries[1] toward each other. In a number of specimens, the graphic structure is developed, usually with the chalcopyrite as the host mineral, and with bornite as the smoothly irregular blebs in it. (Figures 45,46.) When these structures are studied, it is difficult to avoid forming the opinion that

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1. Page 51.

the two sulphides are contemporaneous in origin. In a fair number of cases, however, bornite was observed to form broad margins along gangue veinlets, now altered to calcite, which cut chalcopyrite areas. (Figure 42.). The deduction that this bornite is later than the chalcopyrite follows inevitably, and it is also clear that the bornite is of the same age or later than the original gangue mineral in the vein. No break can be detected between the bornite of the areas showing the mutual boundaries or the graphic structure, and the bornite of the veinlets. The most acceptable hypothesis is that the chief masses of the chalcopyrite and bornite are of contemporaneous origin, but that the bornite continued to form after chalcopyrite deposition had ceased. The question may arise if there is any possibility that the bornite which replaces the chalcopyrite, is of secondary origin, i.e. deposited from cold descending surface waters. In a deposit exposed only to a depth of 200 feet, this possibility cannot be absolutely eliminated, but the slight amount of secondary chalcocite, the lack of any spacial relations between the bornite veins and the chalcocite, the association of the bornite with hydrothermal minerals, and the rarity of bornite as a secondary mineral elsewhere argue convincingly against this view.

The bornite is confined almost exclusively to the dikes or to the igneous matrix of the breccia. The chalcopyrite, however, is not uncommon as seams or finely dissemi-

nated grains throughout the schist inclusions. This may be considered to indicate that the alteration of the schists took place chiefly during the early intense phases of the intrusion, and in the milder phases under which the bornite became of increasing importance, the alterations were confined to the coarser-grained dike rock. The intense alteration of the minerals of the schists to amphibole and augite, with the much slighter development of sericite and epidote is parallel evidence supporting this interpretation, but both of these sets of facts may be due to chemical differences in the rock.

Tetrahedrite, galena and sphalerite occur in small amounts with the bornite and chalcopyrite. The tetrahedrite and galena are probably contemporaneous with the bornite, occuring as scattered blebs or in places abundantly enough to develop small areas of the graphic structure. This is especially noteworthy with respect to the galena. In a few cases the sphalerite contains abundant fine inclusions of chalcopyrite, which suggest an intergrowth.

Secondary products. Chalcocite is not uncommon under the microscope, but it is rarely abundant enough to be visible in the hand-specimen. It occurs sparingly as blebs in the bornite, the two sulphides exhibiting mutual boundaries, but generally it is in veinlets or in rims about the bornite, or less commonly about the chalcopyrite. In these forms it is clearly of replacement origin.

The veinlets of chalcocite penetrating the bornite

are frequently oriented parallel to several crystallographic directions in the bornite, of which two, three or rarely four are revealed on the polished surface, and form a pattern which we have termed the lattice structure. The structure will be described in greater detail for other deposits in which it is a more prominent feature.[1]

Associated with the chalcocite, but more abundantly developed, is chalcopyrite of a second generation, which commonly forms plates penetrating the bornite from cracks or grain boundaries. On the polished surface, the plates appear as strips or spines of chalcopyrite, usually oriented in two or three directions, yielding lattice structures similar to those mentioned above. The later chalcopyrite can be easily distinguished from the earlier. The replacement of bornite by chalcopyrite of this second generation is never complete, and in all cases the outline of the original grain is sharply defined even when against the earlier chalcopyrite (figures 43,45.) The two ages of chalcopyrite are very clearly shown by the replacement of the earlier chalcopyrite by bornite along certain gangue veinlets, and by the partial replacement of the bornite in turn by spines of chalcopyrite developed later along the margins of the same gangue veinlets. (Figure 42.) The development of chalcopyrite of the second generation is accompanied by the formation of numerous small

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1. Engels,p.123; Seven Devils,p.147; Bisbee,p.174; Kennecott, pp.258,261.

cracks, which suggest that the reaction involves a shrinkage in volume. This feature places the chalcopyrite of the two ages in striking contrast. (Figure 45.). The development of the later chalcopyrite slightly preceded the formation of the chalcocite, but the general distribution of the chalcopyrite and its dependence on the same channel-ways as the chalcocite afford clear evidence that the two minerals were produced by the same agencies.

In one specimen, the chalcocite areas are broken by a feathery group of small veinlets, along or related to which are oxidized products and small plates, or blebs of chalcopyrite and bornite. (Figure 41.). In a rough way, the structure is parallel to the bornite-chalcocite lattice patterns in the same chalcocite areas, but the bornite blebs usually do not resemble residues. The intervening chalcocite is clean and free from inclusions of any sort. The relations suggest the possibility that the usual reactions of enrichment may have been locally reversed by a concentration of outward migrating iron, and that this bornite and chalcopyrite in small amount was formed by the replacement of chalcocite.

The tetrahedrite is fairly resistant to the attack of the second generation of chalcopyrite. Spines of the latter in bornite were observed to end abruptly against the sharp contact of a tetrahedrite grain.

The relations in one polished chip suggest that galena alters more readily than bornite to secondary chalco-

pyrite, but the evidence is not entirely convincing.

There is a little covellite with the chalcocite and later chalcopyrite, but it is almost negligible in amount.

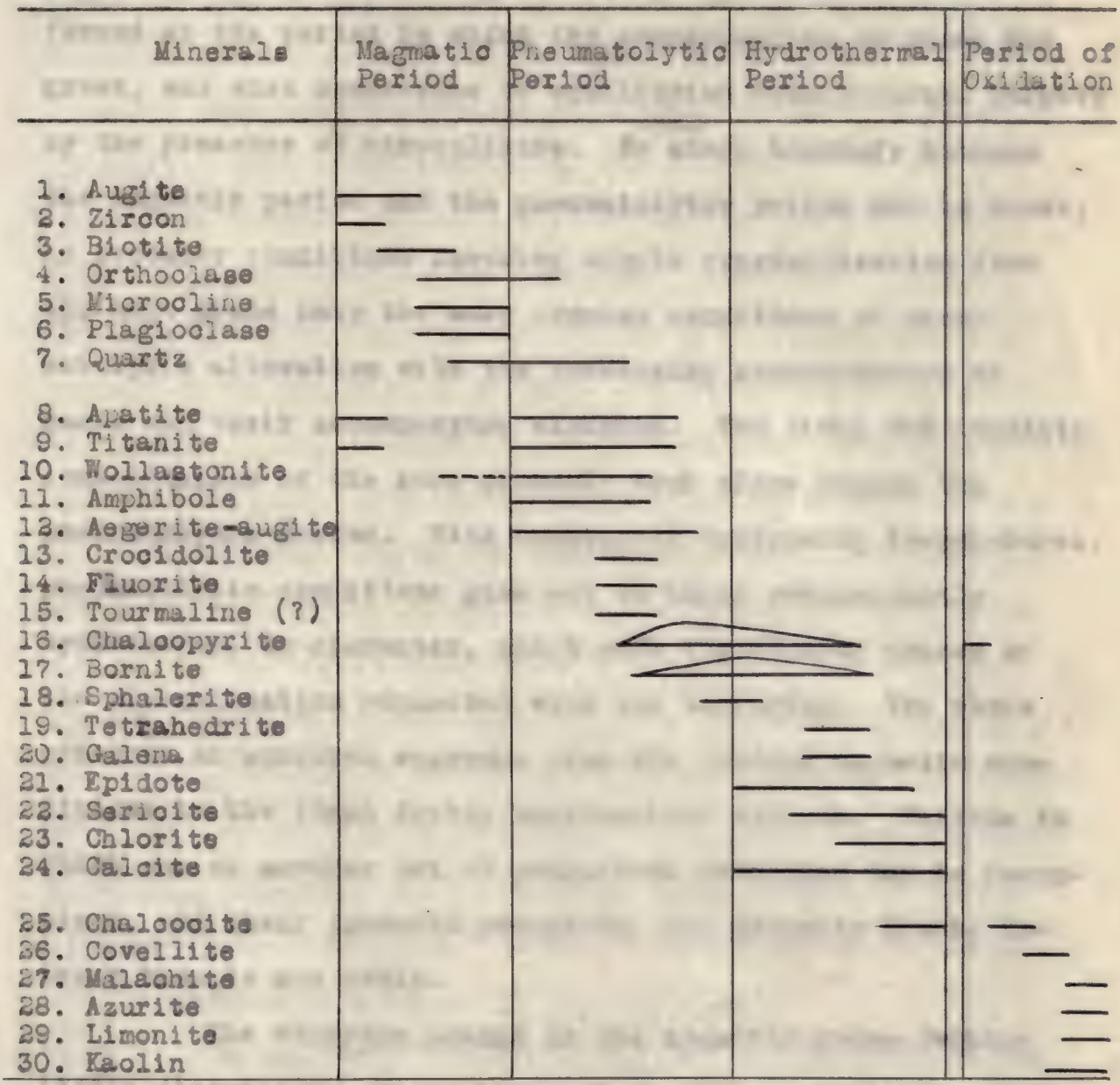
The surface of the ground-water is about 35 feet below the collar of the shaft. Stains of limonite and malachite are common along seams and cracks above it, although the amount of thoroughly oxidized capping is very small, and rarely exceeds a few feet in thickness.

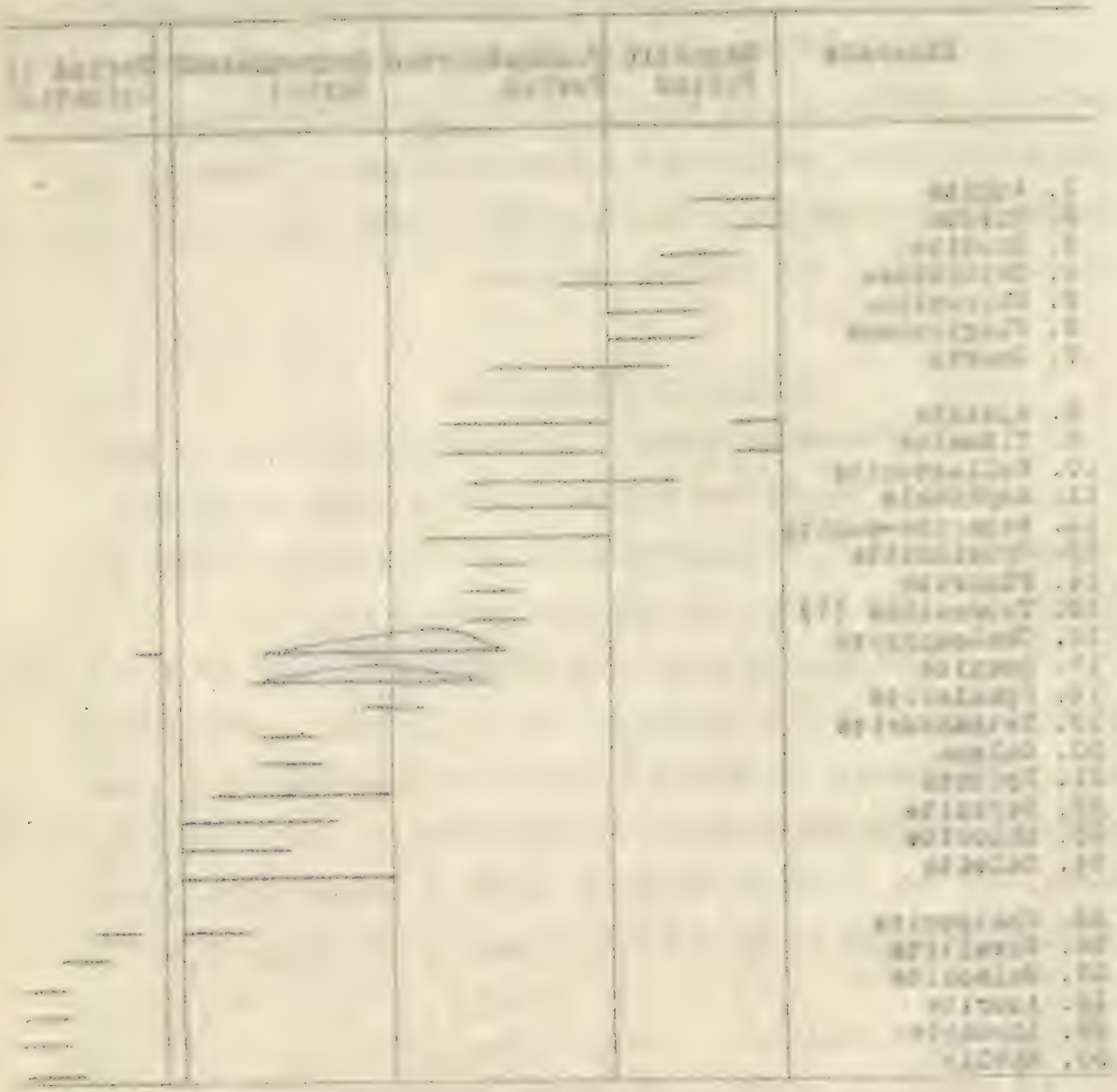
Summary and Discussion.

The minerals observed in the rocks and ores of the Evergreen Mine are listed on the following page, and their sequence, based on the observations presented on preceding pages, is indicated by the lines of the diagram.

It should be noted that the interpretation of the diagram is a little different in the case of the oxidized minerals, and secondary sulphides. All of these minerals are probably forming at the present time in different parts of the deposit, but the order in which they develop at any one point in the ore, ~~however~~, is shown by the lines of the diagram.

Diagram of Mineral Sequence





The minerals grouped as magmatic are those which are believed to have crystallized directly from the igneous melt. Those termed pneumatolytic, are believed to have been formed at the period in which the concentration of gases was great, and when conditions of equilibrium were governed largely by the presence of mineralizers. No sharp boundary between the magmatic period and the pneumatolytic period can be drawn, as probably conditions favoring simple crystallization from the melt grade into the more complex conditions of pneumatolytic alteration with the increasing concentration of gases and their accompanying elements. The final and complete consolidation of the rock probably took place during the pneumatolytic period. With constantly decreasing temperatures, pneumatolytic conditions gave way to those predominently hydrothermal in character, which mark the closing phases of the mineralization connected with the intrusion. The whole presents an unbroken sequence from the initial magmatic conditions to the final feeble hydrothermal effects. Periods in which one or another set of conditions dominates may be recognized, and their products described, but definite breaks between them do not exist.

The minerals placed in the magmatic group require little discussion. Their sequence is that commonly observed in igneous rocks. Both the feldspar and quartz, however, continued to form under the early stages of pneumatolytic conditions, if the occurrence of micropegmatite noted by Rit-

ter[1] may be so interpreted. The large crystals of orthoclase in miarolitic cavities with the sulphides and crocidolite are further indication of the formation of the feldspar under the later conditions.

The aegerite-augite occurs as rims around cores of augite, and is believed to be the result of the shifting conditions brought about by the increasing concentration of volatile constituents. The amphibole, which is developed chiefly in the inclusions and wall rock is probably also a product of pneumatolytic action. Its formation is known to be favored by the presence of hydrous vapors. The crocidolite, which is most commonly formed in cavities of pegmatite dikes may be placed in this group without question. The abundant development of apatite, both in the evergreenite and in the schist, is a further indication of gas concentration, for the existance of notable quantities of the mineral demands the presence of either chlorine or fluorine. Fluorite, which was observed in small grains in miarolitic material, also emphasizes the importance of the pneumatolytic period in the history of the deposit. Tourmaline was doubtfully identified and if present it belongs in this group.

As has been discussed previously, there is reason to believe that the wollastonite is later than the feldspar or the quartz of the evergreenite. Its rarity as a product of direct magmatic crystallization argues against grouping

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1. Loc. cit.

5. See n12.

it with the earlier minerals. It is chiefly found as a contact-metamorphic mineral in limestones, where the abundance of Ca O is undoubtedly a controlling chemical factor, but where at the same time, the physical conditions of formation are controlled by the heated emanations from the intrusion, and are comparable to the pneumatolytic conditions postulated in the genesis of the Evergreen rocks and ores. For these reasons, it seems better to place the mineral in the pneumatolytic group in this case, although the microscopic evidence is not absolutely conclusive that it belongs there. Bastin and Hill describe the ore-body as an endomorphic effect due to contact metamorphism as quoted on page 60 . The interpretation of the wollastonite as a pneumatolytic product is in agreement with their conclusion, although elsewhere in their paper, the impression is given that they regard the mineral as a product of direct crystallization from the melt.

The sulphides are clearly later than the feldspar, quartz and pyroxene, for they unmistakably corrode these rock minerals. The occurrence of the sulphides in the rocks showing greatest concentration of aegerite-augite, wollastonite and apatite, and in rocks with abundant miarolitic cavities, points to their formation under pneumatolytic conditions. The microscopic relations show the sequence of chalcopyrite and bornite to be approximately as indicated by the diagram. (The evidence is given on pages 71-73.) The other

sulphides are hardly abundant enough to give conclusive evidence of their age relations, but they are approximately contemporaneous with the bornite, although probably somewhat more abundant toward the closing phases of its period of formation. It is of interest that the amount of magnetite and pyrite is very small. The little magnetite observed was originally present in the schists. The pyrite occurs only as a few scattered grains, apparently in the schist, and may be the product of other mineralizing conditions, unassociated with the chief mass of the ore-body. Bastin and Hill, on what seems to be good evidence believe another period of mineralization has introduced galena and sphalerite, but neither the field nor microscopic results of my work, give any further information on this subject. The small amount of sphalerite and galena to which reference has previously been made, is probably not what they had in mind.

Epidote, sericite, chlorite, and calcite ~~as hydrothermal minerals~~ have been classified as hydrothermal in agreement with the general interpretation of the conditions under which these minerals form. The close association of bornite and epidote in several cases indicates the continuation of the formation of bornite under hydrothermal conditions, although there is less evidence of its association with the other minerals of the group. In the rich ores, the wollastonite of the evergreenite is invariably replaced by calcite; this special relationship between the sulphides and calcites sug-

gests that the latter is probably a late product of the mineralizing agencies, rather than a result of descending carbonates. The shallowness of unquestioned surface alteration except along narrow seams and veinlets also favors this view. The calcite is later than the sericite or chlorite and may be regarded as the closing product of the mineralizing processes.

The results of oxidation are limited to a small amount of secondary chalcopyrite and veinlets of chalcocite, and to a few feet of malachite and limonite-stained capping.

The Origin of the Deposit. Bastin and Hill state that the dike of evergreenite is an offshoot of the monzonite stock to the east of the mine, and there seems to be no reason to doubt the correctness of their statement. If this is the case, the deposit presents an interesting sequence of differentiations from monzonitic material into an alkaline granite, and locally into the peculiar sulphide and wollastonite bearing rock, evergreenite. A progressive change of this sort may be readily interpreted as a result of pneumatolytic action. The concentration of the alkaline elements in magmas has been attributed to gaseous action by C. H. Smyth, Jr.,[1] who considers water to be the most important and abundant mineralizer.

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1. C. H. Smyth, Jr., The Chem. Comp. of the Alk. Rocks and its Signif. as to their origin, A. J. S., Vol. 36, 1913, p. 33.

Arhenius[1] states that water above the critical temperature would tend to extract CO_2, H_2S, and the univalent ions such as Cl, Fl, B, with some of the strongly positive ions as Na, K, and the rare-earths. With such a mechanism there is good reason to believe that the small residues of valuable metals might become concentrated, and finally deposited in forms rich enough to constitute ores. The entire process is similar to that commonly postulated for the formation of pegmatites. The evidence of the importance of gases — such as the presence of aegirite-augite rims, of abundant apatite, of fluorite and possibly tourmaline, of micropegmatite and the miarolitic cavities — has been presented and discussed on the prededing pages, and it is sufficient I believe to warrent the conclusion that the deposit is predominently of pneumatolytic origin, although the mineralization continued with declining strength under hydrothermal conditions.

The unusual occurrence of wollastonite, however, is less satisfactorily explained by such an hypothesis. Its rarity as a constituent of an igneous rock, or as a pegmatitic mineral suggests that there is probably some peculiar condition governing its formation in this case. Bastin and Hill believe that the high content of Ca O in the magma is due to the reaction of the melt on calcareous country rock. As the sharp boundaries between the included schist fragments and

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1. S. Arrhenius, Zur Physik der Vulkanismus, Geol. Foren. Forh., 22, p. 247, 1900.

the intrusive exclude the possibility of any notable material having been absorbed from the wall rocks at the present surface, they conclude after weighing the various possibilities that the magma probably absorbed the Ca O from calcareous rocks encountered at greater depths.

The explanation of the origin of the deposit advanced by Bastin and Hill is in no way opposed to the conception of a pneumatolytic origin for the ores, and may be enlarged without difficulty to strengthen the idea. According to a theory advanced by R. A. Daly[1], alkaline rocks are the acid pole of the differentiation of a syntectic formed by the reaction between a basic magma and a calcareous rock. A mechaniem, chemical and mechanical by which the introduced Ca CO_3 may react with the magma to form and concentrate a differentiate high in the alkalies is described by Daly[2], and will not be discussed here except those phases of it which may be of direct application.

The increased concentration of Ca O is believed to result in the formation of the comparatively dense lime-iron-magnesium silicates, which tend to concentrate toward the lower portions of the magma, leaving the remaining material relatively richer in the alkalies. An excess of Ca O, which might conceivably separate as the simple silicate, wollastonite,

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1. R. A. Daly, Igneous Rocks and Their Origin, N. Y., 1914, McGraw-Hill Co., p. 430.
2. Ibid., p. 430.

($Ca\ Si\ O_3$) would have little tendency to settle away from the acid pole, as its specific gravity of 2.8 (at normal temperature) is but little greater than that of a monzonitic rock. The importance of the resurgent CO_2 is emphasized by Daly as a condition aiding the differentiation of the magma, and evidence is given illustrating the manner in which the alkalian elements are transported by this gas. Applied to the conditions at the Evergreen Mine, it is evident that the theory offers a common explanation for the alkalian character of the granite dike, the presence of wollastonite, and the pneumatolytic nature of the deposit. The concentration of sulphides of copper and subordinate quantities of other metals may be attributed to resurgent gases, chiefly carbon dioxide and water, provided it is assumed that calcareous rocks have been encountered at depths.

Origin of the Chalcocite. Although the amount of oxidation is slight, it is entirely sufficient to have furnished the very small quantity of copper necessary to have formed the thin rims or veinlets of chalcocite in the bornite. The similarity between the character of the replacement of the bornite, and the association between the chalcocite and the spines of chalcopyrite is very similar indeed to the conditions found in other ore-bodies in connection with chalcocite of known secondary origin, and there is no reason for believing this case to be exceptional. A. F. Rogers[1], in an article on secon-

1. Secondary Sulphide Enrichment of Copper Ores with Special Reference to Microscopic Study, Min. and Sci. Press, Oct. 31, 1914, p. 686.

dary sulphide enrichment, suggests an origin by ascending solutions for the chalcocite at the Evergreen Mine, and publishes a photograph to support this view. It is true that there is a small amount of chalcocite in blebs in the bornite, which is difficult to interpret as an ordinary replacement of the bornite, and which is possibly of an earlier age than the chalcocite forming the veinlets and rims. In one or two cases associated blebs of chalcocite and tetrahedrite in the bornite show a faint tendency toward the graphic structure. If limited to these rather indefinite forms, which surely constitute less than 5 % of the chalcocite present, Rogers' suggestion carries weight, and can not be disregarded. There is nothing in the evidence to eliminate the possibility that this small portion of the chalcocite is primary, but it is fairly certain that the larger part of the chalcocite and the associated chalcopyrite which replaces the bornite is due to the action of descending surface waters. Bastin, in a later article[1] sees no reason for attributing the chalcocite to ascending solutions, and prefers the commoner explanation for it.

Conclusions.

The conclusion that the ore-deposit is the result of the differentiation of apophyses of a monzonitic stock,

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1. The ore-deposits of Gilpin Co., Colorado, Econ. Geol., Vol. 10, (1915), p. 276.

brought about chiefly by pneumatolytic agencies, follows with fair certainty from the evidence. The presence of wollastonite, according to Bastin and Hill, suggests the reaction between limestone and the magma at depth. This conception, enlarged by Daly's theory of the origin of alkalian rocks, offers an explanation for all the observed facts, but it rests upon the assumption of the existance of calcareous rocks in depth, which is impossible to prove or disprove.

The conclusion that the ores and associated dike rocks are of pneumatolytic origin rests on a direct interpretation of definite evidence, and is equally applicably whether the gases are of juvenile or resurgent origin, or both.

The small amount of chalcocite, which is developed entirely in the bornite, is believed to be the product of secondary processes. The origin of an almost negligible amount in small blebs in the bornite cannot be determined.

Copper Mountain, Yale District, British Columbia.

INTRODUCTION

Situation. - Copper Mountain in southern British Columbia is a north - south ridge rising about 1500 feet above the Similkameen River about 13 miles south of Princeton, the chief town of the Similkameen Mining Division of the Yale District. The mineralized portion of the mountain is largely the property of the British Columbia Copper Company, which has thoroughly prospected the deposits by trenches and diamond drills, and is rapidly pushing development work. An attractive camp has been established on the upper slopes of the mountain in the delightful open forest of yellow pine and lodge-pole pine characteristic of this climatic belt. (Fig. 5).

Summary of Previous Work. - The deposits on Copper Mt. were first brought to the attention of geologists by a note published by J. F. Kemp in 1901,[1] in which the bornite was described as a primary constituent of pegmatite dikes, and was stated to be of direct magmatic origin. A microscopic study of the material collected by Prof. Kemp was made somewhat later by Jules Catherinet[2], who describes Copper Mountain as a mass of gabbro, with other eruptives, cut by ore-bearing seams and peg-

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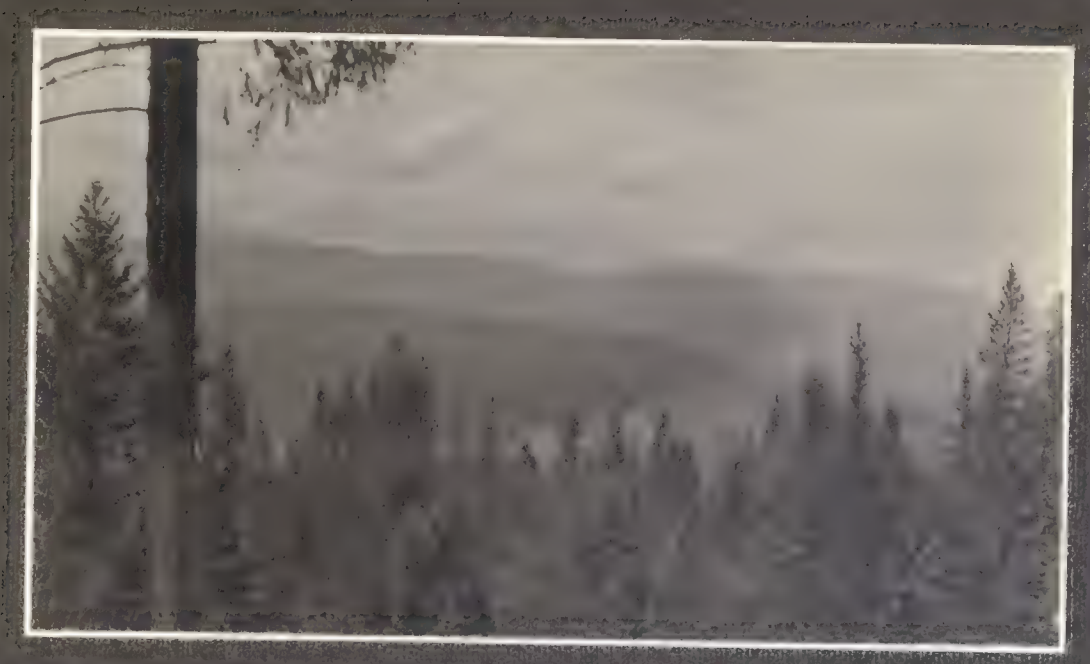
1. Trans. A.I.M.E., Vol. 31, p. 182,(1901).
2. Eng. and Min. Jour., Vol. 79, p. 125-127,(1905).

PLATE III.

Fig. 5. View looking west from Copper Mountain, Similkameen District, British Columbia.

Fig. 6. View looking west from La Fleur Mountain, Danville District, Washington.



matite dikes in the mineralized area. He wrote that the ore occurs in two ways, contrasted but genetically akin. In one, the sulphides form coatings along small crevices, accompanied by little pegmatite seams of the same magnitude as the bornite veinlets. In the other, the bornite occurs in large, typical pegmatite veins exposed on the Copper Cliff Claim. Bornite in masses up to 1/2 cubic ft. were described scattered through the pegmatite. The bornite is accompanied by smaller amounts of chalcopyrite. Orthoclase and biotite are the chief minerals, with smaller amounts of oligoclase, tourmaline, fluorite and calcite and a very little primary quartz. It is stated that the bornite is partially altered to chalcopyrite. Sketches and descriptions make it quite evident that some of the chalcopyrite is of secondary nature, but it seems to me to be very doubtful if this is true for the larger part. The chief argument favoring the magmatic origin of the bornite is its occurrence with unaltered orthoclase and biotite in pegmatite. Calcite is said to be the only mineral present which seems to be an alteration product. It was not observed by Catherinet to have any genetic relations with the bornite. Gold and platinum (as sperrylite) occurring in flakes in bornite and in orthoclase are described. Sperrylite in biotite is also mentioned. Both are believed to be magmatic.

The ores have been described also by D. N. Scott,[1] who

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1. Jour. Canadian Mining Inst., Vol. 5, pp. 493-502, 1902.

emphasizes some structural features. The geology of the region is treated in a very general way by Chas. Camsell[1] in a report of the Canadian Geological Survey.

The geology of the mineralized region on the surface of the mountain has been worked up very thoroughly by S. H. Ball for the British Columbia Copper Company, and certain rock determinations have been made by C. P. Berkey. Their reports however have not been made available for public use.

The geologic sequence according to Mr. Ball's report is as follows:

Pleistocene
(1) Glacial drift;

Miocene
(2) Porphyry dikes (monzonites, quartz porphyry, andesites and others);

Tertiary lavas (nearest a couple of miles away);

Jurassic (?)
(3) Pegmatite and granitoid equivalents;

(4) Granodiorite;

(5) Augite monzonite porphyry, and a gneissic augite monzonite porphyry.

Pre-Jurassic
(6) Altered rocks, in part probably altered sediments.

The sulphides occur in the pegmatites and in various rocks of earlier age. The Tertiary dikes, which are very abundant, are entirely barren, and clearly post-ore. They are far more extensive than the mineralized area, and show no traces of the

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1. Report 986, C.G.S., (The Similkameen District), 1906.

alteration associated with the sulphides.

My information concerning the ores was gained chiefly from an examination along numerous trenches across the mountain and from material on the dumps of shallow shafts. There were no underground workings of importance at the time of my visit, and most of the prospect pits were flooded and inaccessible. I was given the privilege of examining the drill records and the sections drawn from them, and also gained much valuable information from Mr. Patrick Crane, in charge of the property at the time, and from Mr. James Tremlett, an engineer of the company.

ROCKS ASSOCIATED WITH THE ORES.

The sulphides occur most abundantly in a dark medium-grained gabbro. The prevailing rock of the region is granodiorite, and it is probable that the rock associated with the ore is merely a more basic phase of the larger mass. A specimen of the rock remote from ore was found to contain basic andesine and orthoclase with the latter slightly less abundant than the former, and a subordinate amount of quartz. The plagioclase in some grains ranges from a core near acid labradorite in composition to a rim near oligoclase. The chief dark constituents are pale green augite and a somewhat smaller amount of dark brown biotite. Apatite and magnetite are present as accessory minerals. The rock is apparently more basic than the usual granodiorite. Near the ore, the orthoclase be-

comes subordinate or is entirely lacking, and there is usually no quartz. The brown biotite of the more remote rock is lacking, but its place is taken by a green variety. The pyroxene remains abundant as before. The more basic types of this rock would be properly termed gabbro, but in places it seems closer to an augite diorite in composition.

The plutonic rocks are cut by seams of pegmatitic material, usually less than half and inch in thickness but occasionally in small dikes, six inches or more across. In them, pink orthoclase is the chief constituent, usually with a little albite associated with it. Quartz becomes of importance in places, and apatite is usually common. Deep green biotite is rather abundant. . Calcite is usually present, but it is apparently an alteration product. Small irregular segregations of similar material, often very rich in the biotite, occur in the heart of the rock and are probably related to the pegmatites in origin.

The older porphyry of the mountain, termed augite-monzonite porphyry, is somewhat similar in general composition to the associated plutonic rocks, and may be merely an earlier product of the same intrusion. Although the rock is greatly altered by the mineralizing processes in all my specimens, it can be seen that the phenocrysts are plagioclase (oligoclase-andesine (?)) and augite in a microgranitic ground-mass containing abundant orthoclase and a little quartz. The latter may have been due in part to the mineralization. The green-

biotite common in the diorite or gabbro occurs in these rocks also. The presence of the pale augite and the green biotite suggests a relationship to the plutonic rocks.

The dikes later than the ores were not studied. They are fresh, unmineralized fine-grained porphyries for the most part, among which a quartz porphyry is a prominent member.

ORES AND ROCK-ALTERATION.

The ores of Copper Mountain are chiefly bornite and chalcopyrite in approximately equal amounts. The chalcopyrite and bornite are contemporaneous in part, but there is occasionally a little evidence of corrosion by the bornite which suggests that its period of formation lagged a little after the deposition of the chalcopyrite had ceased. A small amount of pyrrhotite was noted in ores from the Silver Dollar claim on the northern end of the mineralized zone. Pyrite is noticably absent. Magnetite occurs but is not abundant. In ores from Voigts' Camp a mile or so from the mountain, specularite is a prominent mineral, but it does not occur in notable amounts with the bornite ores of the larger deposit. A few small blebs of galena were detected under the microscope, but the mineral is of no quantitative importance. The sulphides are disseminated through the gabbro or diorite, or occur as thin seams along slight fractures. The latter are prominent in broken ore, for the rock commonly splits along such cracks, leaving the bornite as a thin film on the face of the block.

In the older altered porphyries and sediments, the ore-minerals appeared to me to be less abundantly distributed and more closely confined to partings or seams. The sulphides also occur in the small seams or dikes of pegmatitic material, and in the mica rich segregations. Although fairly coarse grains of bornite or chalcopyrite are sometimes seen in these associations, the sulphides in the pegmatitic material are of little importance from a quantitative standpoint and constitute only a small fraction of the ore. The copper values lie chiefly in the mineralized gabbro and older rocks.

There is little rock alteration associated with the sulphides in the pegmatite. The ore-minerals are later than the feldspar and biotite, which they corrode or cut in veins, but their introduction is not accompanied by sericite, chlorite or epidote, — minerals which are commonly associated with sulphides of hydrothermal origin. Calcite is often abundant, but appears to be later than the ores.

In the plutonic rocks and the older porphyries, however, there is fairly pronounced alteration where the sulphides are abundant. The grains of bornite or chalcopyrite are commonly bordered by rims of epidote, which is often developed in small amounts elsewhere through the rock. The plagioclase, especially the basic cores of the grains, are usually somewhat sericitized; the orthoclase on the other hand is little altered. Chlorite is not abundant, although it occurs to some extent in the basic constituents. Calcite is wide-spread, cutting the

rock in many small seams, or scattered as replacements of the rock-minerals. It is probably a product of the closing phases of the mineralization. Bornite in small amounts was observed in one calcite seam, which indicates that it continued to form in a feeble way even under these late milder conditions.

OXIDATION AND ENRICHMENT

The surface alteration is very slight. There is a little carbonate staining, but it usually does not penetrate many feet below the surface. The mountain has been severely glaciated, and all traces of an earlier gossan, if such existed, have been removed. The ground-water level is between ten and twenty feet below the surface in most places, and the secondary sulphides are only feebly developed.

Little of the bornite exposed to view is entirely free from traces of the secondary sulphides, but in no place is the enrichment of especial value. The development of veinlets of chalcocite and covellite through the bornite is the chief manifestation of surface changes. These minerals, however, are also accompanied by chalcopyrite, which has developed as fine lattices of intersecting plates, closely similar to the relations described in the ores from La Fleur Mountain. The plates of secondary chalcopyrite range from fairly coarse plates, scattered here and there along veinlets which are easily detec-

ted under low magnifications, to the finest grills of thin intersecting lines on the polished surface which can hardly be detected under the oil-immersion lens. As in the other case described, it seems very probable that submicroscopic chalcopyrite exists in this form which may account for the yellowish tints of some of the bornite grains. The secondary origin of the visible chalcopyrite plates is convincingly shown by the dependence in distribution upon veinlets of chalcocite and covellite.

Chalcocite in the graphic structure with bornite. Besides the chalcocite of easily recognized replacement origin derived by secondary processes, just described, the mineral also occurs in small amounts associated with the bornite in groups of irregular, curved and divided blebs and lobes, which possess a rather definite pattern not unlike that of certain metallic eutectics or of micropegmatitic intergrowths of quartz and feldspar. The relation has been termed the graphic structure.[1] In the bornite from Copper Mountain, the chalcocite in these structures is differentiated from the secondary sulphides previously mentioned by the disregard it shows for the obvious channel-ways which would be sought by replacing solutions, such as grain boundaries, gangue contacts, or small cracks. For the most part, it shows little regularity which would suggest the influence of crystallo-

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1. L. C. Graton & D. H. McLaughlin, Econ. Geol., vol. 12, p. 23, 1917.

[illegible]

graphic forces in its formation, but in a few examples, there is a rough allignment which may possibly indicate such tendencies. These graphic structures in the Copper Mountain ores are usually somewhat modified by chalcocite replacement, but the latter appears to be related to the chalcocite of the veinlets, and superimposed on an older structure. The chalcocite in both structures is bluish and no line can be drawn between them where they intersect. However, the existance of graphic chalcocite in some blebs unassociated with the material clearly of replacement origin, suggests that it is not dependent on the feeble veinlets of chalcocite which represent enrichment from the present surface.

The origin of the chalcocite in these graphic structures is one of the most difficult problems encountered in this investigation. Further discussion will be postponed until later pages, where wider evidence will be available and the many arguments bearing upon its solution can be presented in full.

Discussion and Summary. The sulphides in the pegmatite dikes may be considered primary constituents, but as they are later than the silicates with which they are associated, it is probable that they were formed under pneumatolytic rather than strictly magmatic conditions. The occurrence of tourmaline and fluorite in these ores as mentioned by Catherinet, strengthens this interpretation of origin. The more widely developed ores in the gabbro and older rocks may be attributed with a fair degree of certainty to the same general source, but the

close association of epidote and sericite with the sulphides in most parts of the deposit indicates that the sulphides continued to form and were deposited in greatest abundance under later hydrothermal conditions.

A small amount of chalcocite occurs in graphic structures, and a little in veinlets of undoubted secondary origin. With the latter is associated a small amount of chalcopyrite in lattice forms, some exceedingly fine-grained, and a little covellite.

Engels, California.[1]

INTRODUCTION AND CONCLUSIONS

The Engels copper mine, located in northern Plumas County, California, 27 miles northeast of Keddie on the Western Pacific Railroad, lies at an elevation of about 5,200 feet on a gentle, forested slope that descends toward the southwest from the crest of one of the eastern ridges of the Sierra Nevada. The property has been worked more or less steadily for many years, but has suffered because of remoteness from rail transportation and of difficulty in either smelting or concentrating the bornite-chalcopyrite ore which it chiefly yields. The installation of an oil-flotation plant and a vigorous campaign of underground development have recently brought production to a higher level than previously attained.

Preceding these recent developments, a geological examination of the deposit was made by Mr. H. W. Turner, and specimens which he collected were studied microscopically by Prof. A. F. Rogers, of Stanford University. The results of their investigations, published as a joint paper,[2] merit particular

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1. Taken with little change from an article entitled Ore Deposition and Enrichment at Engels, California, by L. C. Graton and D. H. McLaughlin, published in Econ. Geol., Vol. XII, pp. 1-38, Jan. 1917.

2. Econ. Geol., Vol. 9, pp. 359-391, (June, 1914).

Chapter VIII.

Introduction to Philosophy.

attention because of the two principal conclusions which the authors reach, viz.: (1) that the ores are of direct magmatic origin, and (2) that the development of chalcocite and some covellite by replacement of bornite is the work of ascending, heated alkaline waters and is thus to be regarded as an example of "upward secondary enrichment."

The accelerating tendency in recent years to ascribe the origin of many ore deposits to igneous influences must be admitted to rest more on reasonable inference and on elimination of objections than upon direct and positive evidence. Any instance in which sulphide ores have been formed in syngenetic relation to the enclosing igneous rock therefore assumes special interest and significance. The importance thus given to the Engels occurrence was only increased by a paper by T. T. Read,[1] who, after a brief visit to the deposit, concluded that the magmatic origin of the ores is not certain.

Still more interest, if possible, attaches to the Engels deposit in connection with the origin of the chalocite. The idea of "upward secondary enrichment," though it had been earlier hinted at or somewhat vaguely invoked to explain certain observations, was proposed as a definite hypothesis for copper sulphide ores in an earlier paper[2] by Professor Rogers. That paper was virtually an announcement of the hypothesis and an

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1. Mining and Scientific Press, July 31, 1915, pp. 167-171.
2. Econ. Geol., Vol. 8, pp. 781-794, Dec., 1913.

[illegible]

[illegible]

PLATE IV

Fig. 7. The Engels Mine, California, showing the various tunnel entrances.

Fig. 8. The outcrop of the Engels Mine California, above upper tunnel.

application of it to the deposits of Butte, in advance of the complete description of an unnamed occurrence which, in Professor Rogers's opinion, afforded the most convincing proof of the hypothesis. This hypothesis was immediately accepted and adopted by the corps of able and assiduous investigators at Stanford and has already been given by them a conspicuous place in the literature. Among interested students elsewhere, the expected article by Professor Rogers that should deal with specific evidence of upward secondary enrichment in a carefully studied example was awaited with interest; it proved to be the paper on the Engels mine.

In a later article, Professor Rogers had somewhat revised his first ideas, especially in recognizing that part of the Engels chalcocite is due to the normal process of descending enrichment. In consequence, some of our evidence upon this important point is merely confirmatory, as is indeed the case with regard to many of the other matters discussed. There remains, however, sufficient divergence of views as in our opinion to warrant presentation of all our evidence.

With regard to the two principal questions involved in the Engels occurrence, we conclude as follows:

1. The ores, instead of being magmatic in the sense that they were initial constituents of the dioritic rock in which they occur, were introduced after the rock had solidified and had suffered notable dynamic and chemical changes,

and constitute replacements formed under pneumatolytic and hydrothermal conditions. The deposition of the sulphides was an intermediate episode in a complex and unusually complete sequence of magmatic phenomena and after-effects that began with crystallization of the parent rock and ended with the formation of zeolites and carbonates.

2. Although the possibility of formation of a small amount of chalcocite from ascending solutions cannot be absolutely excluded, no satisfactory evidence of chalcocite of replacement origin formed in this way, i.e., by "upward secondary enrichment," has come under our observation. Most of the chalcocite and all of the covellite at Engels unquestionably result from replacement of earlier sulphides through the agency of descending meteric waters, and a competent explanation for all of the chalcocite is to be found in normal downward enrichment.

GENERAL DESCRIPTIVE TREATMENT - COUNTY ROCK, ORES, AND ALTERATION.

Magmatic Period.

Solidification of Norite. - The Engels ore-deposit occurs in a body of rather dark, medium-grained plutonic rock, which is probably a basic differentiate of the great Sierra Nevada

batholith of granodiorite. The rock was nowhere seen in its original condition, but it may confidently be inferred from its altered phases that it was noritic in character, being composed of plagioclase and slightly subordinate amounts of orthorhombic and monoclinic pyroxenes, and biotite. The feldspar varies somewhat in character, but usually it is near an acid labradorite in composition (Ab_1, An_1). Bronzite, hypersthene, and diopside are present in quantity that approximately equals the feldspar, while the biotite is usually subordinate in amount, although its small laths are occasionally plentiful. Zircon, apatite and euhedral magnetite are common accessories.

The form of the body of norite is not definitely known, as surface croppings are scarce, and its contacts with the surrounding rock of the batholith can not be traced. Underground, on several levels, in passing out of the ore, siliceous rocks are encountered, which possibly mark the limits of the norite body in those directions. In a cross-cut off Tunnel 4, one of these light-colored, acidic rocks is encountered, and proves to be a granodiorite porphyry. The rock is characterized by large feldspar phenocrysts, set in a medium to fine grained ground-mass, consisting chiefly of unstriated feldspar and biotite. Under the microscope, the "phenocrysts" are seen to be composite, consisting of aggregates of smaller laths of andesine, of about the same grain as the constituents of the ground-mass (Figs.53 and 54).

The ground-mass is chiefly orthoclase, quartz and biotite with an accessory amount of plagioclase. This somewhat acid rock may reasonably be interpreted as another variant of the granodiorite batholith but of subordinate importance.

Pneumatolytic Period.

Alteration of Norite. - After the crystallization of the norite, a period ensued in which conditions of equilibrium were apparently disturbed, probably by increasing concentration of water and other mineralizers; this may be termed the pneumatolytic period. The magmatic products were partially altered into minerals more stable under the new conditions; chief among these is amphibole, formed in part at the expense of the pyroxenes, while the labradorite underwent partial recrystallization with attendant cracking and straining, and the production of rims of more acidic varieties, oligoclase and albite. The resulting rock may be regarded as a peculiar type of diorite, or perhaps more properly as a meta-norite. This derivative of the original norite is more extensive than the ore-bodies and constitutes the principal country rock of the Engels mine. The amphibole is chiefly a light green hornblende, but locally, along seams and in segregations, laths of actinolite were formed. The hornblende is widely developed throughout the rock, but it is more abundant and in largest crystals in the ore-bearing portions. It forms large, strikingly poikilitic crystals,

frequently containing corroded cores of pyroxene, but extending far beyond the original limits of the pyroxene crystals, and including numerous rounded grains of labradorite and small particles of the accessory minerals (apatite and magnetite). Slightly corroded laths of biotite are frequently included in the large crystals. In many cases, the inclusions are so abundant that their total volume is considerably greater than that of the amphibole host.

Formation of Segregations. - The formation of small lens-shaped segregations in the norite (or diorite) is clearly related to this period of pneumatolytic alteration. They probably represent the products of the late crystallization of small localized concentrations or residues after the crystallization of the normal magmatic minerals. In these segregations, actinolite and albite are the chief minerals, although in a few cases, biotite assumes an equal importance. In one interesting occurrence, a lenticular mass, over eight inches in diameter and approximately two inches thick, occurs in the fine-grained dioritic rock. The outer layer of this segregation consists of stubby, green laths of actinolite, and it is succeeded inward by a well-marked zone of albite, in coarse anhedra. This in turn surrounds an inner core which was originally an aggregate of actinolite, albite and large crystals of titanite. In this and in most of the other segregations studied, the cores and frequently the outer layers are largely replaced by chlorite, epidote and calcite, with associated copper ores, but these changes are clearly

subsequent to the formation of the segregations themselves. The amphibole is always earlier than the albite, the latter being molded about the well-formed prisms of the former in many cases, but it is later than the biotite, except that locally, where the biotite is especially abundant in a segregation, the order may be reversed.

Formation of Pegmatites. - In a few places underground, the workings expose narrow pegmatite dikes cutting the diorite. They are composed chiefly of acid feldspar and subordinate quartz, with a small amount of actinolite, usually concentrated near the edges or developed in the adjoining wall rock. Chalcopyrite, but rarely bornite, is associated with the pegmatites, as intermittent central bands, or as disseminated grains in the neighboring diorite. In one specimen from a one-inch dike exposed in a drift to the northeast off Tunnel 4, microscopic examination shows the feldspar to be albite-oligoclase, with small cores of a more basic type. With it are pale green laths of actinolite, with subordinate amounts of quartz, titanite, and apatite. A persistent band of chalcopyrite along the center of the dike is the only sulphide in this case. In another specimen from a larger dike, the pegmatite was found to be composed of quartz, microcline, and small amounts of labradorite, titanite, and a deeply pleochroic hornblende, with a few crystals of tourmaline. Patches of chalcopyrite and bornite occur in it, and appear to be original constituents.

Dynamic Changes. - A pronounced straining and shearing of the feldspars, accompanied by recrystallization in various degrees, is notable throughout the rocks studied. In many cases, no traces of these changes are found in the large amphibole crystals, although the surrounding and included feldspars show wavy extinction (see Fig. 52) and partial granulation. In other cases, the amphibole itself may lose its fresh, coarse-grained character, and become reduced to shreddy masses of variously oriented fibers, often distinctly uralitic in appearance. It may therefore be inferred that the straining and accompanying recrystallization took place within the pneumatolytic period, although locally it may have continued longer, or even have started somewhat later. The recrystallization is not confined to the diorite, but is also well shown in the neighboring siliceous rocks. An excellent example is the breaking down of the phenocrysts of the granodiorite porphyry into an aggregate of andesine crystals, as is clearly shown in the two photographs (Figs. 53 and 54). In several of the specimens, a distinct schistose structure has been produced by the grouping of the recrystallized biotite laths in bands. The feldspar assumes a crystalloblastic texture in these cases, but the grains of the pyroxenes show little change. Where the recrystallization is most intense, apatite is abundant, forming elongated clusters of rounded grains of distinctly different habit from the ordinary magmatic apatite. In one or two slides, a subparallel arrangement of plagioclase laths may be attribu-

ted to the flowage of the partially crystallized magma, but superimposed on this structure are changes similar to those previously described, which can be satisfactorily explained only as the result of stresses acting on the rigid rock. The fractured apatite crystal in Fig. 52 is striking evidence of dynamic action.

Development of Iron Oxides. - Associated with the more intense phases of the development of the amphibole, but for the most part a little later, is magnetite, in large masses with abundant inclusions of apatite. This iron ore is clearly later than the small euhedral grains of magnetite, accessory in the norite, which were included by the growing crystals of the pneumatolytic hornblende. The later magnetite occurs commonly molded about the amphibole forms, occasionally slightly corroding them, and in a few cases it is so abundant that the crystals of hornblende appear as if set in a cement of magnetite and apatite, with a relatively subordinate amount of rounded feldspar grains and a little spinel (see Fig. 59). The pneumatolytic origin of this magnetite is indicated by its close relationship with the development of the amphibole, and this view is confirmed by the abundant apatite and by the occurrence in several instances of small crystals of tourmaline in close association with the magnetite.

With the magnetite, and perhaps in part a little later in origin, occur ilmenite and hematite. Intergrowths of all three minerals have been observed, while those of ilmenite and hematite are very common, occurring in nearly all of the

polished chips studied. In these intergrowths the hematite is usually subordinate, and appears most commonly on the polished surface as fine white lines, in parallel orientation in one, or more rarely, two directions. Other sections show the hematite as elongated, narrow ovals or as dots scattered with a rough regularity through the ilmenite. The magnetite occasionally contains plates of hematite, and now and then occurs in rather patchy inclusions in ilmenite-hematite areas, the fine white lines of hematite passing uninterruptedly through the magnetite as well as the ilmenite. These minerals were determined by mineralographic methods,[1] and the presence of ilmenite was confirmed by obtaining titanium tests from gravity concentrates from the crushed specimens.

Development of Pneumatolytic Sulphides. - The most important phase of mineralization, as far as the value of the ore is concerned, is that which is characterized by the development of chalcopyrite and bornite. In most cases, these sulphide ores are accompanied by notable hydrothermal alteration of their host and are therefore described under a subsequent heading, but in a few specimens, they occur in remarkably fresh feldspathic rock. They are clearly later than the rock minerals, which they surround and slightly corrode, and are in places so abundant that the rounded grains of plagioclase and laths of biotite appear as if set in an opaque cement (Fig.51). In relative smoothness of outline, the sulphide

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1. J. Murdoch, Loc. cit.

grains resemble those of magnetite. These sulphides seem to be analogous to the ores in the pegmatite, previously mentioned, and are regarded as the earliest in origin which we have observed. The structure might readily suggest a magmatic origin for the chalcopyrite and bornite, but, on more careful examination, occasional laths of chlorite and sericite may be seen included in the sulphide grains, and, where the sulphides are in contact with the plagioclase, thin borders of albite are found. In the material which best exhibits these relations, the bornite occurs as definite seams, near which the impregnation of the rock with ore is greatest. Along these seams the rock readily breaks apart, yielding fracture faces completely coated with bornite.

This pneumatolytic stage is the nearest approach to magmatic conditions that is shown by the development of the sulphides, for the earlier minerals such as the labradorite and biotite remain fairly resistant to the introduced material, but the presence of the hydrothermal minerals, and the fracturing of the rock, indicate that strictly magmatic conditions had passed.

INTENSE HYDROTHERMAL PERIOD.

Development of Chlorite, Sericite and Epidote. - The commonest type of sulphide ore, however, is indicative of slightly milder conditions than those of the pneumatolytic period just described. Chlorite, sericite, epidote and cal-

cite become more and more important. The chlorite is especially characteristic, occurring as blunt laths or slivers included in the bornite or chalcopyrite, or occasionally as complicated tangles of small laths, with the sulphides both as acutely angular areas between them and as thin wedges extending along the cleavage of the chlorite. Rogers first regarded the chlorite as earlier than the bornite but in his later paper he states that the chlorite is younger than the bornite and replaces it. Our evidence is in essential accord with the first view and we are unable to follow Rogers's argument in favor of the second. In some cases, the bornite distinctly corrodes the chlorite laths (Fig. 66). Moreover, it is generally true that the direction of the chlorite laths is not in accord with the structure of the bornite as revealed by natural alteration or by etching. On the other hand, many of the laths appear unattacked, and probably are virtually contemporaneous with the bornite. The chlorite was frequently found between the magnetite individuals, some of which are well crystallized (Figs. 57 and 58); it was never observed as inclusions in the magnetite. The biotite is partially or completely replaced by chlorite, especially where the latter is well developed with the ores. The amphibole also suffered a partial alteration to chlorite, and in many cases amphibole crystals are fringed with ragged borders of chlorite and bornite, or are penetrated by veinlets of these two minerals. The large hornblende crystals in Fig. 57 well illustrate this type of alteration.

The sericite is largely confined to the basic plagioclase, but occasionally it is more widely developed, and bears a relation to the bornite very similar to that shown by the chlorite. Fine laths and slivers of sericite are included in the bornite or chalcopyrite, usually near the edges, less commonly in the heart of the grains. In both of Rogers's papers, the sericite laths penetrating the bornite are regarded as having replaced the sulphide, but we have failed to find evidence supporting this view. It seems to be much more in accord with the usual criteria of sequence to regard them, like the chlorite, as inclusions in the bornite. Apparently the bornite and the sericite developed at about the same time; the bornite commonly started first, accounting for the usual absence of sericite in the cores, but toward the edges of the grains, the sericite formed as laths a little ahead of the last outermost parts of the bornite, in which they are therefore included. Sericite is not abundant in specimens which on other grounds are regarded as examples of the earliest sulphides, and this is in accord with the view just expressed. The basic feldspars are most thoroughly altered to sericite, while the more acid rims or recrystallized portions usually remain untouched. The biotite is slightly attacked by the sericite, but to a greater extent it is altered to chlorite, as is conclusively shown by the presence of residual sagenite webs in certain large areas of chlorite. In a few instances, the lath-shaped inclusions of chlorite and sericite in the ores may likewise

have been derived from corroded biotite or remnants of amphibole, but this explanation will not hold for the majority of cases since the inclusions are in general distinctly different in habit from the original brown biotite or the amphibole of the rock. Although it is impossible to reach a positive conclusion concerning the relative ages of the chlorite and sericite, there is a suggestion that part of the chlorite is a little older than the sericite, for the kind of corrosion by bornite shown by chlorite laths has not been certainly observed in the case of the sericite; also the chlorite is less noticeably confined to the outer margins of the bornite grains than is the sericite.

Epidote is also a common associate of the sulphides. In some cases veinlets of it cut chlorite (Fig.63), but for the most part the two minerals are apparently contemporaneous. The epidote may form fringes about grains of bornite and chalcopyrite; elsewhere it occurs in euhedral forms about which the sulphides are molded (Fig.56). In many places, the amphibole is greatly altered to epidote, and veinlets or irregular patches of the latter are common as replacements in the feldspars. A few veinlets have been observed cutting magnetite. Ragged areas of fine-grained epidote, thickly filled with small grains of bornite or chalcopyrite, and with more or less chlorite are found here and there in greatly altered specimens.

Development of Hydrothermal Sulphides. - The commercial ore at Engels is distributed in somewhat indefinitely-bounded shoots, of which several have been opened and which collectively constitute a deposit of roughly elliptical plan within the

modified norite. As a rule the ore merges into the country rock and all gradations exist from scattered minute sulphide grains to heavy masses of ore with subordinate gangue.

The bornite and chalcopyrite, which are the most abundant ore minerals of the Engels deposit, were formed mainly under hydrothermal conditions, together with a small amount of enargite, tetrahedrite and sphalerite. Magnetite, ilmenite and hematite, which apparently had continued to develop during the early portion of the period of bornite formation, ceased to form as conditions became milder, and became surrounded or rarely veined by the bornite and chalcopyrite which continued to increase. The bornite is about three or four times as abundant as the chalcopyrite.

For the most part, the contacts between the chalcopyrite and bornite offer little evidence of the sequence of the two minerals. Broad bays of chalcopyrite extend into the bornite or smooth projections of the bornite penetrate the chalcopyrite, but in many cases if the forms of the two minerals were interchanged, their relations to each other would be little altered. The term mutual boundary has been found useful in referring to the line of contact of minerals in this association (Fig.67). There is evidence, however, that the chalcopyrite slightly preceded the bornite, as inclusions of the former are commoner in the latter than the reverse, even where the two sulphides occur in equal amounts, and in a few cases the chalcopyrite shows slight corrosion by the bornite. Nevertheless, for the greater part of their periods of forma-

tion, they were probably contemporaneous.

As the proportion of the chlorite and epidote grows, indicating increased departure from magmatic conditions, the ores become more and more ragged and irregular, and in the thin section are easily distinguished by their form alone from the more regular magnetite grains. They seem also to have exerted a greater corrosive action on the rock minerals, the amphibole especially suffering, although the other constituents are not spared.

The enargite occurs sparingly with the other sulphides, and is apparently of about the same age. Tetrahedrite is perhaps a little commoner and its presence may account for the slight silver value of the ore. It occurs in the same relationship to the bornite and chalcopyrite as the enargite. A few minute grains occuring in hornblende were identified as galena.

Calcite is abundant in most of the specimens. It clearly replaces amphibole and feldspar, and is associated with the epidote in an intimate way, veinlets of each cutting the other. The calcite had a longer range, however, extending into the period of later hydrothermal conditions. Rogers mentions finding calcite as a late magmatic mineral. In our thin sections, the calcite is clearly a replacement of earlier minerals, (Fig. 61) although in certain areas the replacement is so complete that, if evidence from other portions of the slide had not revealed its true character, it might have been mis-

taken for an earlier constituent of the rock. In no case, however, was there the least doubt of its distinctly later character.

LATE HYDROTHERMAL PERIOD.

Development of Zeolites and Carbonates. - One of the most interesting phases of the rock alteration is the development with the carbonates of a series of zeolites, as a late hydrothermal product. The following members of the group were definitely determined, by means both of thin sections and of index liquids: scolesite, analcite, heulandite, natrolite, and laumontite. Thin radial aggregates of thomsonite and small patches probably of chabazite and phillipsite were identified in thin sections only, but the minerals are not present in sufficient quantities to permit of their determination with absolute certainty. A little prehnite, found in only one section, is probably a product of the same conditions as the zeolites. The minerals of the zeolite group are fairly widespread, occurring in over one third of the specimens studied.

In one specimen, scolesite has completely replaced the plagioclase, whose former presence is indicated only by the zeolite-filled molds of magnetite, which had shaped themselves about the original feldspar laths. A surprising feature is the presence of unaltered hypersthene, bronzite and diopside in this greatly altered rock; having apparently escaped the alteration to amphibole in the pneumatolytic period, the pyrox-

ones remained resistant to the zeolitizing conditions. The scolesite also forms a veinlet half an inch wide of finely radial, white fibers, and in it are a few grains of bornite, which show the feeble extension of the bornite forming conditions into the period of the zeolites.

The commonest type of zeolitic alteration is the replacement of feldspar by heulandite, and in about half of the cases, the subsequent replacement of the heulandite by natrolite. The analcite in the rocks was observed by Rogers, who regarded it as a primary constituent. In one or two instances, it occurs as shapeless grains, which give no clue to their origin, but in other cases it seems unquestionably to be a replacement of feldspar, and its association with the other zeolites confirms this view. Calcite or siderite is usually present, replacing even the latest zeolites, although occasionally they are themselves cut by veinlets of natrolite.

Our evidence is not sufficient to permit the entire list of zeolites observed to be grouped in the precise order of their formation, but the analcite and heulandite are clearly earliest, with natrolite, laumontite, and thomsonite forming a later group. The relative positions of the others are in doubt. The carbonates are persistent, and in many places the completeness with which they replace the preceding minerals has greatly obscured the evidence of the earlier relationships. Siderite is less common than calcite, but it is frequently found as a border about calcite grains, being readily distin-

guished by its much higher relief, better crystal form, and slight iron staining where exposed to oxidation. It is not established with certainty, however, that the siderite is a member of this mineral group formed under late hydrothermal conditions; the possibility that it is a product of descending oxidizing solutions will be considered later.

PERIOD OF OXIDATION AND ENRICHMENT.

Between the period of the formation of the zeolites and the exposure of the ore to the influence of oxidation, the ore-bearing rock was again broken by series of roughly parallel cracks, which became filled with fine veinlets of siderite and calcite. The breaks are abundant in certain zones, and almost lacking in others. They show no relation to the earlier shearing and straining of the rock. All minerals and structures previously described are broken by them, except that they show a marked avoidance of bornite grains which lie in their paths. Occasional carbonate veinlets cut through the bornite, but far more commonly they are diverted, and pass around the border of the sulphide grains. On the other hand, the magnetite and ilmenite-hematite intergrowths are greatly cracked, as if they were more brittle, and are penetrated by the veinlets wherever these are notably developed. The earlier shearing and recrystallization of the rock, and the later fractures occupied by veinlets were of great importance in facilitating the downward movement of sur-

face solutions by which oxidation and descending secondary enrichment were accomplished.

Zone of Complete Oxidation. - The outcrop of the Engels deposit, which lies at an elevation of about 5,500 feet, is wholly inconspicuous. (Figs. 7 and 8). A mantle of granular soil conceals the rock except at a few places where slightly copper-stained croppings are exposed but do not project noticeably above their surroundings. The orebody is capped by a moderate but irregular thickness of oxidized and leached rock. Plainly this material once contained sulphides for it is stained by limonite, malachite and chrysocolla, and is cut by banded seams and small veins of these minerals. In these veinlets, the silicate seems to have been the last to form, frequently breaking across the carbonate bands, and building out as knobby, botryoidal forms into open spaces presumably formed by removal of the sulphides.

Zone of Sulphide Enrichment. - According to Mr. Juessen, who was in charge when the upper parts of the orebodies were developed, the zone of complete oxidation changes irregularly into a zone of mixed carbonate and chalcocite ore, rich portions of which were mined, but caving has made these uppermost stopes now inaccessible. This was succeeded immediately below by a much more definite and regular zone of chalcocite ore, of which much the largest and richest portions were discovered subsequent to the examination made by Mr. Turner. Ore of this kind was found in a locus averaging about

twenty-five feet thick, and dipping approximately parallel to the surface, which slopes rather gently to the southwest. A very considerable tonnage of such chalcocite ore was mined out, with values up to 16 per cent. copper, and an average grade materially higher than that of the ore at greater depth. In general, this ore gradually fingered out at depths of about 90 to 130 feet below the outcrop into ore consisting essentially of bornite, but occasional stringers and bunches of chalcocite ore extend considerably deeper.

In nearly all the chips studied, chalcocite was found in varying amounts, commonly as a replacement of bornite and to a very small extent a replacement of chalcopyrite. Its most striking development is in connection with the veinlets of carbonate previously discussed, and this relationship persists to the deepest workings of the mine (June, 1916), a winze 125 feet below the level of No. 4 Tunnel or about 375 feet from the surface. In many cases chalcocite occurs only where the bornite is broken or bounded by such veinlets. The abrupt manner in which laths of sericite are cut by the veinlets with which the chalcocite is associated, leaves no doubt of the independence of origin of the chalcocite from the sericite. Veinlets of chalcocite are frequently observed to take advantage of the presence of included laths of chlorite or sericite along their course, breaking from one to another, while other laths nearby, but not intercepted by the veinlets, may be sharply bounded by the bornite without a trace of chalcocite. Where

the bornite occurs in small ragged slivers in aggregates of epidote, chlorite or sericite, the enrichment is most complete, due both to the greater permeability of the rock at such places, and to the relatively greater surface of bornite exposed by the finer grains. Chalcocite is commonly well developed also where the bornite is penetrated by laths of chlorite or sericite, although occasionally no enrichment is observed in connection with these minerals. Our studies of chalcocite formation in many districts indicate that enrichment favors the contacts between primary sulphides and gangue minerals (Fig. 74), because of the greater local permeability along these junctions, and that micaceous gangue minerals, as sericite or chlorite, notably promote both local and general enrichment, as Beeson has so clearly shown in the case of Bingham.[1]

In addition to the replacement of bornite along irregular veinlets and grain boundaries, the chalcocite also replaces that mineral along crystallographic planes. Where this type of replacement is well developed, the polished surface reveals a strikingly regular pattern, consisting of three intersecting systems of narrow strips of chalcocite, separated by triangular and rhombic residues of the bornite; the well-known relationship which is termed the lattice structure.

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1. Beeson, J.J. T. A.I.M.E., Vol. 54, pp. 402-441. 1915.
54 402-441

Associations of bornite and chalcocite in graphic structures are present sparingly throughout the deposit as now developed, except where the bornite has been completely converted into chalcocite (Figs.69,70,75 and 79). These graphic structures at Engels occur in the midst of bornite masses away from fractures and grain boundaries, and they also occur in the marginal portions of bornite areas as well as adjacent to veinlets of chalcocite from which the graphic chalcocite is not separated by any visible demarcation. The question of the origin and significance of these graphic structures, which is one of considerable complexity, will be given attention on a subsequent page.

Covellite is occasionally produced in subordinate amounts by partial marginal replacement of bornite and chalcopyrite. In a few places, either in chalcocite near bornite or in the bornite itself,it forms fine lines on the polished surface, which show the same structural control by the bornite as has been described for the chalcocite and bornite in the lattice structure. Examples are clearly illustraded by sketches and photographs in Turner and Roger's paper.

Secondary chalcopyrite is found to a relatively small extent. It is commonly associated with chalcocite, but appears to prefer small cracks or nooks in the bornite somewhat removed from the paths of strongest chalcocite development. The replacement of bornite by chalcocite involves the removal of iron as well as the addition of copper, and the small isolated

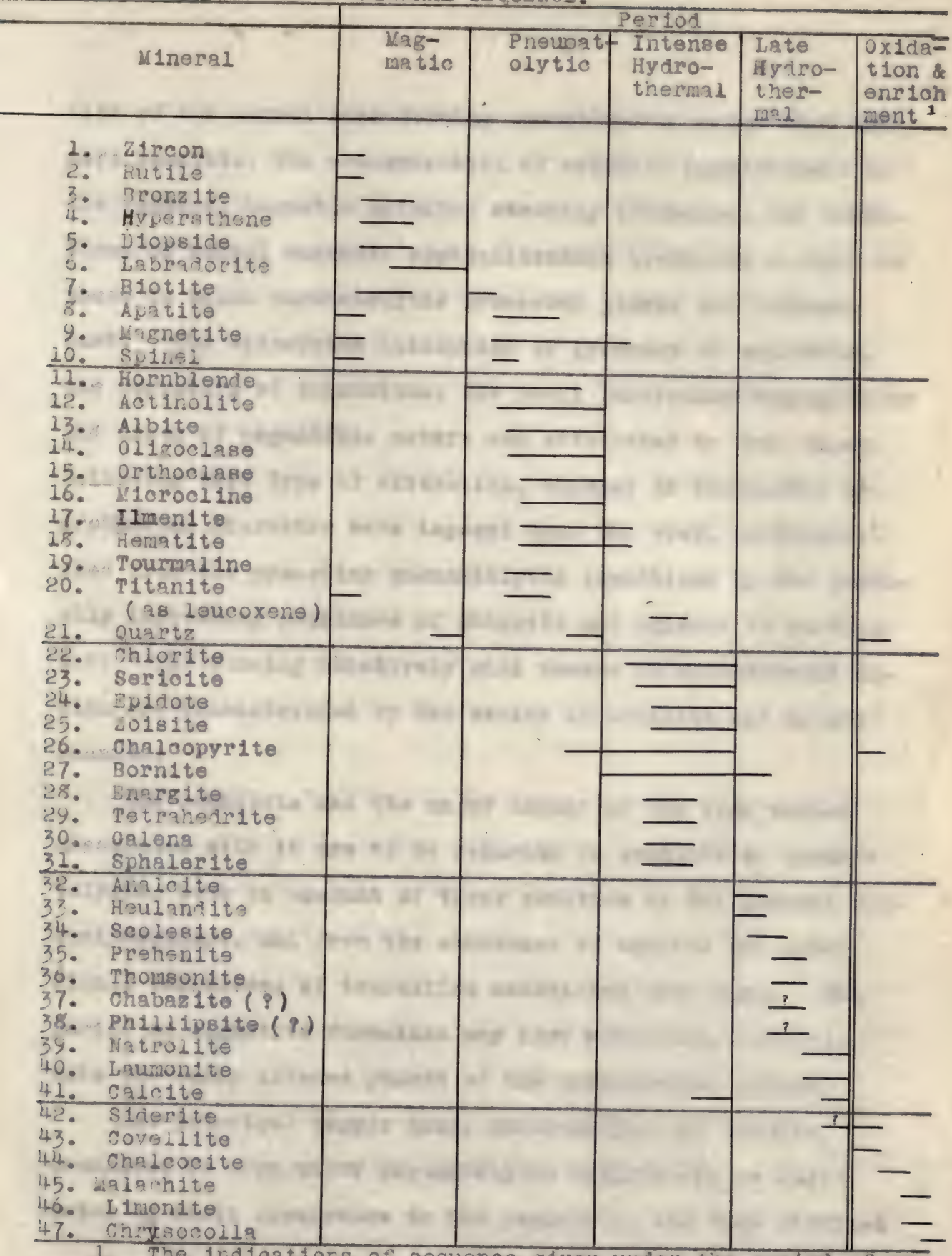
veinlets or spines of chalcopyrite probably represent local concentration of iron — small eddies, as it were, in the main stream of enrichment — where conditions of equilibrium were temporarily reversed, and the iron-rich sulphide formed. The chalcopyrite frequently penetrates the bornite along definite structural lines, producing in some cases a lattice pattern similar to that described for chalcocite and for covellite in bornite (Fig. 77). Inasmuch as various stages have been observed from a few isolated spines penetrating the bornite from the edge of a veinlet of chalcocite due to downward enrichment to the well-developed lattice-work, there can be no doubt that these chalcopyrite spines are of the same origin as the chalcocite. In the specimen which shows the most striking development of secondary chalcopyrite, the high concentration of iron and the influence of surficial conditions are indicated by the development of a strong seam of limonite, to which the distribution of the chalcopyrite shows a definite relationship.

DISCUSSION.

Genetic Classification of the Deposit.

The grouping of the minerals (p.123a) is merely a summary of the interpretation of the genesis of the deposit presented on the preceding pages, and so needs little further discussion. The magmatic group includes only the minerals which crystallized directly from the differentiated magma. As the separa-

DIAGRAM OF MINERAL SEQUENCE.



1. The indications of sequence given under the period of oxidation and enrichment are intended to show the progressive arrival of various influences at any given horizon. In reality, probably all the minerals of the period have been forming, at one part or another of the deposit, from the beginning of oxidation to the present.

tion of the normal rock-forming constituents became more and more complete, the concentration of volatile constituents in the residual magmatic material steadily increased, and conditions of normal magmatic crystallization gradually changed to those in which pneumatolytic processes played the dominant part. The widespread alteration of pyroxene to amphibole, the formation of tourmaline, the small lenticular segregations and dikes of pegmatitic nature are attributed to this phase. Following this type of alteration, changes of distinctly hydrothermal character were imposed upon the rock, differentiated from the preceding pneumatolytic conditions by the gradually increasing abundance of chlorite and epidote in particular. The closing relatively mild phases of hydrothermal action are characterized by the series of zeolites and by carbonates.

The amphibole and the major amount of the iron oxides associated with it are to be regarded as products of pneumatolysis, both on account of their position in the general mineral sequence, and from the abundance of apatite and occasional inclusions of tourmaline associated with them. The period of magnetite formation may have continued, however, into the early intense phases of the hydrothermal period.

The principal copper ores, chalcopyrite and bornite, commenced to form under pneumatolytic conditions, as indicated by their occurrence in the pegmatite, but they attained

their maximum development when accompanied by minerals of accepted hydrothermal origin, and even continued in a feeble way into the period characterized by the zeolites. The percentage of the ores connected with the pegmatites, or as occasional small inclusions in the magnetite, is small, and there seems to be good evidence that the larger part of the sulphides - the part which makes the deposit a commercial orebody - is of hydrothermal origin.

Turner and Rogers regard the ore as a magmatic segregation. From field evidence, Turner considers the sulphides to be the final products of the crystallization of the magma, analagous to the quartz in a granite, and to have been formed before the development of the pegmatites. As a matter of fact, such a view is justified by the general appearance of much of the ore and by many of the broad field relations, though it is contradicted by certain megascopic features, subordinate in distribution but significant in character, such as the schistose structure of some of the ore-bearing rock, and the presence of sulphides both along fractures, and in seams of pegmatite and rarely of zeolites. Rogers concludes, from microscopic examination of Turner's specimens, that the ores are products of gaseous solutions, rich in mineralizers, and evidently assigns to them a later origin than did Turner. Although pointing out that deLaunay groups deposits of such origin under the heading

Gîtes de départ immédiat, Rogers retains the term "magmatic segregation," because of the close analogy he believes to exist between the ores at Engels and those at Sudbury, Insizwa and other deposits that are commonly regarded as magmatic segregations.

The phase in the geologic history of the Engels deposit which seems to us to correspond most closely to the conditions of origin postulated by deLaunay for the deposits classified by him as Gîtes de départ immédiat, is what we have termed the pneumatolytic period. The iron oxides at Engels and a small proportion of the bornite and chalcopyrite were formed at this stage. They might possibly be classified as magmatic segregations provided the term may properly be expanded to such an extent. But the close association of the greatest part of the primary copper sulphides with hydrothermal minerals is distinctly different from the conditions as described for Sudbury or other deposits regarded as magmatic, and unquestionably classifies the Engels orebody as a hydrothermal deposit.

ORIGIN OF THE CHALCOCITE.

Chalcocite Clearly of Replacement Origin. - Rogers first attributed the formation of chalcocite at Engels entirely to the agency of ascending alkaline waters and considered it a hydrothermal effect. In his later publication he recognizes that chalcocite due to descending waters is present, but maintains that "the evidence in favor of 'upward enrichment' is even stronger than before." The absence of kaolin, the occur-

rence of chalcocite in massive ore-bearing rocks, and the relation of the chalcocite to the sericite and chlorite are points he has urged to support the thesis of "upward secondary enrichment." They may be considered in order.

The absence of kaolin was advanced in Rogers's first paper as a proof that the chalcocite is not the product of descending solutions. Confirming his observations, we find that it is not a common product at Engels, although small amounts were found in a few cases. The formation of kaolin[1] depends primarily on the presence of sulphuric acid, which in turn is largely derived from pyrite. As no pyrite has been observed at Engels, the lack of kaolin with the oxidized products is not surprising. The solutions descending from the oxidized zone are probably at most only mildly acid, as they do not noticeably attack the carbonate present in the rock or even in the veinlets with which chalcocite is associated, but there is no reason to believe that such solutions are incapable of producing chalcocite enrichment. Our observations in many districts indicate that the enrichment of bornite to chalcocite by descending waters is accomplished so readily, and with the production of so little sulphuric acid,[2] that it may take place without the appreciable development of kaolin.

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1. The generalizations in this paragraph regarding kaolin have been drawn in large part from investigations being carried on by our associate, Edward H. Perry.

2. Zies, E. G. Allen, E. T., and Merwin, H. E., "Some Reactions Involved in Secondary Copper Sulphide Enrichment," Econ. Geol., Vol. 11, p. 500, 1916.

Chalcocite is frequently developed from bornite at Engels in hard, dense rocks beyond the limits of the oxidized materials, but notwithstanding the great ease with which bornite is enriched, this transformation is even here dependent upon the degree to which chlorite and sericite, or microscopic fractures have materially augmented the normal permeability of the ore due chiefly to minute channelways along gangue boundaries.

In his first paper, Rogers assigned an earlier age to the chlorite than to the bornite and chalcopyrite, or the chalcocite, but stated that the sericite is younger than the bornite and chalcopyrite, and that it developed simultaneously and in intimate genetic association with the chalcocite. In his later article, the chalcocite which he attributes to ascending solutions is considered older than both the chlorite and the sericite, while the chalcocite which he ascribes to descending influences is regarded as younger than these gangue minerals. Both kinds of chalcocite, he adds, were formed independent of the process of sericitization, and he now accepts Beeson's explanation of greater permeability to account for the close positional relation observed between the sericite and chlorite and some of the chalcocite.

As we interpret the evidence, the chlorite and sericite laths are to be regarded as inclusions in the bornite-chalcopyrite matrix, yet formed at practically the same time as their host, and perhaps developed with more perfect outline chiefly

because of their greater power of crystallization. We find no satisfactory foundation for Rogers's view that the laths of sericite and chlorite have been formed by later replacement of the bornite and chalcopyrite. We are convinced that this is not true for the chlorite. As for the sericite, however, the evidences (pp.112 and 113) controverting his interpretation are not so abundant or so forceful, and our dissent from it arises as much from its incompatibility with the tendencies of sequence in sulphide ores in general and from the notable similarity of habit and occurrence between the sericite and the chlorite, as from any compelling evidence against it in this particular case.

With respect to the chalcocite, except for the comparatively small amounts in the graphic areas which will be discussed later, the evidence is conclusive that it is later than the sericite or the chlorite. The greater general development of chalcocite in those parts of the ore containing abundant sericite and chlorite is readily explained as a result of the greater permeability caused by the presence of these micaceous minerals, as already noted.

Between the chalcocite in the lattice structure[1] on the one hand, which Rogers regards as due to ascending alteration, and on the other hand the chalcocite of admittedly descending origin which constitutes more or less regular rims

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1. See Fig. 8 of Rogers's article in Econ. Geol., Vol. 11, p. 582, 1916.

about laths of chlorite and sericite[1] and grains of other gangue minerals[2] or forms veinlets[3] with or without accompanying siderite or limonite, we find it impossible to draw any important distinctions as to genesis, and we are forced to conclude that both kinds of chalcocite were formed in essentially the same manner and by essentially the same means.

Examination of Rogers's Fig. 2, to which reference has been made, and of our Fig. 74 reveals the presence of numerous narrow tongues or spines of chalcocite extending from the chalcocite rims into the bornite cores and arranged in several systems of directions. This feature, which is very common at Engels, we have found in many districts to be simply an early stage of the development of the lattice structure. Moreover, this formation of lattice chalcocite in bornite, the development of narrow gashes or spines of chalcopyrite, with or without chalcocite or covellite (Fig. 78) in bornite near where it is being altered to chalcocite, and the similar production of either felted aggregates or sharp plates of covellite along bornite-chalcocite boundaries are features very common in connection with the alteration of bornite to chalcocite by the normal process of downward enrichment, as is exhibited in such unquestionable examples as Bisbee, Morenci, Globe, Ajo, Bingham, and Ely. The last two of these features, furthermore,

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1. See Fig. 5 of same paper by Rogers.
2. See Fig. 2 of Rogers's paper and Fig. 74 of this paper.
3. See Fig. 73 of this paper.

have been produced artificially in the Geophysical Laboratory by the action of solutions containing copper sulphate and sulphuric acid on bornite.

Added to these evidences favoring a descending origin for the chalcocite are several others. The chalcocite, though developed in part by replacement of chalcopyrite, is yielded mainly by bornite; in other words the bornite is much more easily enriched than the chalcopyrite. This is entirely in accord with repeated observations in examples of unquestioned downward enrichment and with the results of experiments in artificial enrichment.[1] In this connection it may be noted that in the conversion of bornite to chalcocite, only a relatively small addition of copper is required to produce a result of important magnitude, for the one mineral contains 63.33 per cent. copper[2] or almost 4/5 as much as the other, viz., 79.86 per cent. Furthermore, the oxidation and leaching of a zone of solid bornite ore would liberate and make available for enrichment at greater depth more than twice as much copper as would a solid chalcopyrite ore of equal thickness. Thus, as regards quantity of chalcocite produced, bornite is doubly at an advantage over any of the sulphides poorer in copper.

In the particular case of the Engels deposit, <u>all</u> the

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1. Zies, Allen, and Merwin, Loc. cit., pp. 498-499.
2. Allen, E. T., "The Composition of Natural Bornite," Am. Jour. Sci., Vol. 41, pp. 409-413, 1916.

chalcocite thus far encountered could have been produced, through enrichment of the original sulphides, by a decidedly smaller amount of copper than has plainly been removed from the upper, oxidized zone, notwithstanding the incompleteness of leaching; and although quantitative data obviously are unavailable, it is not improbable that this source was sufficient, even though the enrichment process may have been wasteful of copper. In any event, it is evident that the Engels deposit once continued above the present surface and, as appears later, topographic conditions were favorable for enrichment during the erosion that cut down to the present outcrop. The copper furnished by leaching of a relatively small thickness of the ore now eroded away, added to that removed from the present leached zone, would unquestionably suffice to account both for any reasonable degree of waste in the enrichment process and for an extension of enriching chalcocite in gradually decreasing abundance to a very considerable depth below the horizon to which the mine workings have yet been carried.

As a matter of fact, if <u>all</u> the chalcocite at Engels be regarded as due to descending waters, the amount of enrichment is moderate or slight as compared with that in other bornite-rich deposits of comparable physiographic history.

Finally in the upper parts of the mine, there are associated with the chalcocite, veinlets of limonite and of siderite (with perhaps a little quartz), while at greater depth, the limonite disappears but the siderite persists. These pro-

ducts thus disposed are what might be expected to result from iron-bearing solutions at different distances from the source of oxygen supply, i. e., the surface, and of course the fixation of iron in a partly or completely oxidized condition in the circulation channelways at either horizon accords with the idea of replacement of a copper-iron sulphide by a copper sulphide under conditions of descending, oxidizing[1] enrichment. Siderite, associated with a little chalcocite, has recently been described at Bisbee[2] as the deepest product of oxidizing influences. In the Bisbee occurrence, the siderite is largely a replacement of calcite (limestone). At Engels, the siderite in the veinlets is pretty certainly a product of surface influences; but as to the siderite that appears to replace areas of calcite in some of the zeolite-bearing rocks, we are somewhat in doubt whether it likewise was formed by meteoric waters or is a final product of hydrothermal action. Whatever its origin, the total amount of siderite at Engels is insignificant.

Covellite, which at Engels is wholly subordinate in quantity to chalcocite, is a replacement of earlier sulphides, and, like the replacement chalcocite, is competently explained

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1. See Spencer, A. C., Jour. Washington Acad. Sci., Vol. 3, pp. 70-75, 1913. Also Graton and Murdoch, loc. cit., p. 65.
2. Bonillas, Y. S., Tenney, J. B., and Feuchère, Leon, "Geology of the Warren Mining District," Bull. A.I.M.E., Sept., 1916, pp. 1451 and 1457.

on the ground that it is of superficial origin. We are unable to follow Rogers's argument that chlorite replaces covellite, but find that covellite, like chalcocite, may replace bornite and chalcopyrite along the margins of chlorite laths and along gangue boundaries in general.

In short, we find at Engels that all the clearly enriching chalcocite - that plainly formed by replacement of earlier, leaner sulphides - is to be explained as a result of the action of superficial solutions, and that there is no need or justification for resorting to the idea of "ascending secondary enrichment."

Chalcocite in the Graphic Structure. - The discussion under the preceding section applies to the chalcocite which gives ready evidence of having been derived by replacement of bornite (and a little chalcopyrite), and only when all the chalcocite of the deposit has been mentioned has reference been intended to the chalcocite that occurs in graphic relation to bornite. This graphic chalcocite is present in amount decidedly subordinate to the chalcocite clearly of replacement origin.

In our opinion, the validity of the hypothesis of ascending origin for part of the Engels chalcocite hinges on the source and character of the chalcocite in the graphic structures. Concerning the origin of the graphic relations between bornite and chalcocite, which have been observed in several districts, a marked diversity of opinion results from the difficulty of the problem and the conflicting nature of much of the evidence.

The ~~problem~~ problem of their origin however will be considered in detail on later pages, where more general evidence will be presented than that offered by the Engels deposit, alone.

If the replacement origin of the graphic chalcocite at Engels is to be accepted, as urged by Rogers, we find no reason whatever for differentiating it in any essential respect as to source and age from the chalcocite of clearly replacement origin which we believe is unquestionably due to secondary enrichment of the orthodox kind. But if the graphic chalcocite is a result of descending enrichment, we believe it represents the feeblest effects of that process and is an exceedingly delicate manifestation of bornite replacement. Possible light on this idea is afforded by conditions at the Superior deposit.

THE SUPERIOR MINE.

An instructive parallel to the occurrence of the ore at the Engels Mine is offered by the neighboring deposit known as the Superior. The hydrothermal character of the ore is very definitely shown in the latter, and the idea that the Engels ore is to a large extent of pneumatolytic and hydrothermal origin, is greatly strengthened by the many points of similarity between the two deposits.

The Superior orebody is situated about two miles to the southwest of the Engels Mine, and approximately 1,200 feet

lower in elevation. The ore outcrops on the steep eastern side of a cañon, several hundred feet above the stream near the lower camp at the foot of the aerial tramway from the Engels mill. Aside from the diamond drill holes, the only development on the property in June, 1916, was a shaft about forty feet deep, but a tunnel was being started lower on the slope to intersect the ledge. The orebody consists of veins of massive bornite and magnetite, ranging from thin seams up to a width of six inches or more. They are spaced a foot or so apart in a fracture zone 10-12 feet wide. The lode as a whole seems to have a high dip, but the individual veins are more or less irregular.

The surrounding rock is a diorite, and is part of the same large plutonic body in which the Engels ore occurs. It is however lighter in color than the rock near the larger mine, and examination shows it to be of more acidic character. The feldspar is andesine with rims of oligoclase or oligoclase-albite, and the hornblende is less prominent than in the darker rock. The veins are accompanied by intense rock alteration. The development of amphibole, chiefly actinolite, at the expense of the feldspar or the original hornblende, is the earliest phase of the mineralization. Apatite in large crystals and titanite in numerous irregular grains are abundant, and were probably produced at this time.

Quartz in varying amounts is common under the microscope, but is not prominent in the hand-specimen. It probably commenced to form with the amphibole. The acidic rims of the feldspars may also be products of this early phase of the mineralization. The feldspar, some of the quartz and the amphibole all show the effects of intense stresses. The amphibole, especially, is fractured and sheared. The bornite and its associated minerals are clearly later and take advantage of the channelways thus afforded. The formation of the sulphides was accompanied by the abundant development of small laths of a green mica, and of epidote, chlorite and sericite. The green mica is commonly a replacement of feldspar or of amphibole, and the sericite, the least important from a quantitative standpoint, is largely confined to the feldspar. The latest mineral of the primary sequence is heulandite, which occurs abundantly as a replacement of the plagioclase.

Bornite and magnetite are by far the most abundant ore minerals. The magnetite appears as large grains sometimes boldly euhedral, surrounded by a cement of bornite. The latter also occurs as fine blebs or irregular veinlets in the magnetite; it is clearly of later age and in part a replacement of the iron oxide. The association between the two minerals is more intimate than in the Engels ore, and the magnetite seems to have been more generally attacked by the bornite than is the case in the larger deposit (Figs.85 and 86). The absence of specularite and ilmenite is noteworthy.

Chalcopyrite is less plentiful than at Engels. A few small blebs of galena were observed.

Chalcocite is present in subordinate amount intimately associated in all cases with the bornite. In small part, it occurs as veinlets and tongues which are clearly replacements. In a few cases, imperfect lattice structures are developed. Chiefly, however, it is in graphic areas or in irregular patches with mutual boundaries, and in these forms, it commonly shows a complete independence of the contacts between the bornite and magnetite (Figs. 86, 88). Where this chalcocite intersects laths of chlorite included in the bornite, the line of contact is in many cases likewise ignored (Fig.86). In some cases, however, no break can be discerned between chalcocite of the graphic areas and adjacent chalcocite of the replacement type.

Clearly of later age than the more abundant chalcocite just described is a bluish variety of the mineral in tiny veinlets cutting the bornite. Where these cut bornite-chalcocite graphic areas, it is sometimes found that the veinlet appears in the bornite lobes but is not distinguishable in the chalcocite blebs. With the chalcocite in these veinlets, there is a small amount of covellite, malachite, and limonite. A little kaolin and limonite are the only products of surface alteration in the wall rock. The slope upon which the orebody outcrops is very steep, and almost devoid of soil. There is no zone of oxidized material, although faint limonite and

malachite stains extend to the bottom of the shaft. The bornite occurs directly at the surface, with only the merest traces of alteration.

The form of the deposit (viz., a definite lode in the diorite) and the nature of the associated minerals (including actinolite, epidote, chlorite, sericite, and heulandite) indicate that the ore is epigenetic, as pointed out by Turner, and of hydrothermal origin. The early formation of amphibole, the dynamic modification of the rock, the subsequent introduction of chlorite, epidote and sericite accompanied by bornite, and the development of heulandite in the closing phases afford, together with the absence of pyrite, a striking similarity to the sequence and character of the minerals at Engels. The occurrence of the ore in a well-defined lode, the greater abundance of the green mica, the closer relationship between the magnetite and bornite, the slightly greater rock alteration, and the unimportance of products of oxidation and enrichment at Superior are the chief points of difference.

Conclusions as to the nature of most of the chalcocite at Superior rest on the interpretation of the same kind of graphic structures between bornite and chalcocite as are shown at Engels, and the discussion of this subject on pages 134 and 135 applies to both deposits. At Superior, however, it is clear that the chalcocite in these forms is not the product of enrichment from the present surface. The small

amount of oxidation under the active mechanical erosion to which the deposit is now subjected may be measured by the feebleness of the veinlets of blue chalcocite and covellite and the slight development of limonite and malachite. Most of the chalcocite is clearly of an earlier age than the veinlets, and, if a product of descending secondary enrichment, it must have been produced under previous topographic conditions. The surface of gentle relief in this immediate neighborhood upon which were deposited the extensive Tertiary gravels of the Jura River[1] appears to have been not far above the present surface at Engels, while perhaps as much as a thousand feet above the Superior outcrop of to-day. There is distinct evidence of at least two later stages in the topographic development, respectively shown by the relatively gentle slopes and open valleys of the higher levels, and the deep V-shaped cañons of the larger streams.

Down at the Superior deposit where the deep incision of the country by an active stream permits only the feeblest present enrichment, most of the chalcocite may be interpreted as the deep roots of an older enrichment formed at a time of less violent degredation. At Engels, where the ore has not yet been reached by the severe erosion of the present cycle,

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1. Diller, J.S., Bull. U.S.G.S., No. 353, Plate II.

there is a moderately thick cover of oxidized and impoverished material, underlain by a layer of rich chalcocite, and still deeper, by plentiful chalcocite that clearly replaces bornite. Although the vertical range of the Engels mine workings is too small to afford conclusive evidence, there is a distinct indication that with depth, the chalcocite of undoubtedly replacement origin decreases in proportion to that in the graphic structures. It may be expected with a fair degree of certainty from the topographic and microscopic evidence that with increasing depth at Engels, the character of the chalcocite will become more and more similar to that observed in the Superior ores. In other words, it is believed that the relations of the chalcocite and bornite exposed in the Superior deposit are similar to the relations between the two minerals in the deeper unexposed portions of the Engels orebody. It is to be noted, however, that this inference is not necessarily dependent upon the interpretation given the graphic structure.

SUMMARY.

The Engels deposit presents an unusually complete record of the varied conditions to which the rock has been subjected from its initial crystallization to the last feeble hydrothermal changes and to the subsequent alterations by surface agencies. The history of the deposit may be summarized as follows:

1. Crystallization of a basic differentiate, of noritic character, from the batholith of the Sierra Nevada. The granodiorite porphyry also probably appeared at this time.

2. Local development of pegmatites; also pneumatolytic alteration of the rock, generally widespread, but occasionally emphasized along seams, producing amphibole, albite, tourmaline, magnetite, and some sulphides, accompanied and perhaps followed by straining, and partial recrystallization.

3. and 4. More localized mineralization and alteration produced under hydrothermal conditions, intense at first, but gradually diminishing, characterized by chlorite, sericite, epidote, and sulphides in the earlier stages, and by zeolites in the closing phases, with increasing dependence upon fractures.

5. Subsequent cracking of the rocks and ores.

6. Exposure of the deposit by erosion to oxidation, with the production of an impoverished oxidized zone and the development of secondary sulphides.

The first four stages, covering the time from initial magmatic conditions to the close of primary mineralization, are merely convenient divisions of one uninterrupted sequence, while the fifth and sixth were separated from the others, and probably from each other by indefinite time intervals.

In the primary sequence, the presence of mineralizers such as boron and either chlorine or fluorine is indicated at an early stage by the occurrence of tourmaline and apatite, but the chief mineralizer from the beginning to the end was undoubtedly water. Its influence in the early stages is suggested by the presence of amphibole, and the development of the zeolites is conclusive proof of its presence at the close. Much of the rock alteration is probably merely the readjustment of the materials of the rock into forms more stable under the influence of the water vapor or water at high temperatures, without notable additions of new elements, except the iron, copper, titanium and sulphur to form the ore minerals. The orebody is in our opinion a direct result of igneous action, but was formed as a final concentration following the crystallization of the rock, and not as a direct magmatic segregation.

Secondary enrichment, which followed the exposure of the deposit to oxidizing influences, accounts for all the chalcocite present, with the possible exception of the relatively small amount in the graphic structure, which also we are inclined to attribute to downward enrichment.

These conclusions find support in the conditions exhibited at the nearby Superior deposit and in certain physiographic features of the region.

CONTACT METAMORPHIC DEPOSITS

Seven Devils, Idaho.

The ores of the Seven Devils district, Idaho, offer definite evidence of the position of bornite with respect to the silicates formed during contact metamorphism, and present good examples of several important structures of bornite and the secondary sulphides. The district was not visited in connection with this investigation, and the field relations given in the following paragraphs were summarized from descriptions by Waldemar Lindgren[1] and by J. B. Umpleby.[2]

The rocks of the Seven Devils district consist of slate, quartzite, limestone and large amounts of associated greenstone, intruded and altered by a quartz diorite phase of the Idaho granite. The series is capped locally by Columbia basalt. The ore-deposits occur along the contact of the quartz diorite and limestone in place, or about the margins of included blocks of limestone.

The most abundant gangue-minerals are garnet, epidote and quartz. Bornite and chalcopyrite are the chief ore-minerals.

In three mines the sulphides occur on the limestone side of the garnet zone. They are connected with the intrusive by means of veins dipping at a low angle, which cut

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1. W. Lindgren, 20th Ann. Rep., U.S.G.S., Pt. 3, pp. 249-253, 1900.

2. J. B. Umpleby, The occurrence of ore on the limestone side of garnet zones, Univ. of California Publication, Depart. of Geology, Vol. 10, pp. 25-37, (1915).

across the altered intervening rock. The veins have been followed by

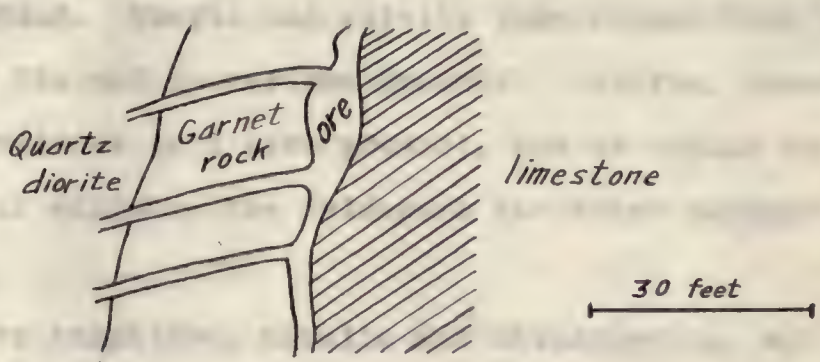

Fig. 9. Transverse section showing relation of ore to garnet zone, Seven Devils, Idaho.[1]

mining operations only to the diorite contact, but they are known to penetrate the igneous rock for at least 25 or 30 feet without diminution.

At the Peacock Mine, the ore occurs in the central part of a large garnet-epidote area bordered on two sides by diorite and on the south by an engulfed block of greenstone. A drill-core shows the centre of the mineralized area to contain unaltered limestone at depth, thus affording another example of the occurrence of sulphides between the limestone and the contact silicate rocks.

From the microscopical study, the sequence of ganque and ore-minerals may be established in a general way as follows. Orthoclase, amphibole, pyroxene (diopside), garnet and apatite constitute a group formed under the early intense phases of the mineralization. Epidote and titanite,

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1. J. B. Umpleby, Ibid.

are probably somewhat later in origin, and chlorite lags still further behind. Quartz and calcite were formed from the beginning to the end in various amounts. Calcite, however, is most prominent as a late product, and is common as a replacement of epidote, the feldspars and other earlier minerals.

The sulphides, bornite and chalcopyrite, are later than the first group of minerals, and later than the epidote, but they are probably in part contemporaneous and in part earlier than the chlorite, quartz and calcite. These relations, supported by the field distribution of the ore-minerals, indicate that the sulphides were formed during milder phases of the mineralization. than those under which the high-temperature contact silicates were deposited.

The amount of secondary alteration which the ore has suffered is not great, but there is a small amount of chalcocite, covellite and chalcopyrite of secondary nature in nearly all the specimens of bornite studied. The chalcocite occurs for the most part in small irregular veinlets or rims about bornite grains and in these forms can be attributed without hesitation to the agency of descending surface solutions It also occurs, however, to a minor extent in graphic structures with the bornite and in a few larger patches in massive bornite in which it is less certainly of replacement origin. In these forms, the chalcocite apparently possesses the ortho-

hombic structure, for in a few cases the characteristic pattern of straight lines oriented parallel to one direction is shown by the etch-cleavage and by malachite veinlets.

The structure of the chalcocite in the rims and veinlets is less definitely shown by etching, but lattice patterns are frequently formed in it by the development of covellite and oxidized products. The replacement of bornite by chalcocite yields imperfect lattice structures in a few places, but it is not a common relation between the two minerals in these ores.

Chalcopyrite is abundant as fine plates in the bornite, which form usually well-developed lattice patterns on the polished surface. The chalcopyrite is more widely distributed than the chalcocite, but it is clearly related to the same channel-ways and is without doubt the product of the same solutions. The relations are very similar to those previously described in the ores from Engels, La Fleur Mountain, and Copper Mountain in the Similkameen region. In some grains, the plates of chalcopyrite are so fine and so closely spaced that they can be detected only with difficulty under the highest magnifications, and it is very probable that the peculiar yellow tint of certain spots in the bornite from Seven Devils is due to sub-microscopic chalcopyrite of this character.

Plates of covellite assume lattice orientation in both the bornite and in the derived chalcocite. In places,

the covellite is an intermediate product in the replacement of chalcocite by malachite.

In summary, the deposits at Seven Devils are believed to offer very convincing evidence both from the field and microscopic relations that the bornite is later than the high-temperature contact silicates. The development of chalcopyrite, in exceedingly minute lattices, and its dependence on the development of secondary chalcocite and covellite is exceptionally well shown, and the inheritance of structure of the bornite by the chalcocite is strongly suggested by the formation of covellite in the lattice structure in the chalcocite.

The origin of the small amount of chalcocite in the graphic structure can not be settled from the evidence in this case alone, and will be discussed in a more general way in a later part of the paper.

The Whitehorse District, Yukon Territory.

In the contact-metamorphic ores of the Whitehorse District, Yukon Territory, bornite is the most abundant sulphide. The district was not studied in the field in connection with this work, but from information gained from R. G. McConnell's excellent descriptions[1], and from an examamination of material in the collection of the Massachusetts Institute of Technology the occurrence is believed to be of sufficient value as an example of bornite formed under contact-metamorphic conditions to be worth summarizing.

The district is situated in the valley of the Lewes River in the southern part of Yukon Territory near the town of Whitehorse, the terminus of the White Pass and Yukon Rail Road, which affords communication with Skagway on the Lynn Canal, 110 miles to the south.

The various formations in the copper belt may be tabulated as follows:

Pleistocene - Silts, boulder clays.

Tertiary - Basalts.

Mesozoic - Porphyry dikes, granites, porphyrites.

Carboniferous - Limestone.

Of these rocks, only the limestone and the plutonic intrusives are of interest in connection with the ores.

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1. The Whitehorse Copper Belt, Yukon Territory, Report No. 1050, C.G.S., (1909).

The earlier porphyrites are rarely mineralized, and the porphyry dikes are always barren and clearly post-ore.

The granitic rocks are believed to be outliers of the Coast Range batholith. They are extraordinarily varied in their mineralogical composition, ranging from hornblende granite to diorites, hornblende and augite syenites and even to gabbros. The commonest phase is the hornblende granite. It is a medium to coarse-grained rock consisting essentially of quartz in grains of various size, orthoclase and hornblende. A little andesine or oligoclase, augite and biotite are usually present. Magnetite, ilmenite, titanite and apatite are the less abundant accessories. Micropegmatitic intergrowths of quartz and feldspar are mentioned, but are stated to be of uncommon occurrence.

The limestones are moderately crystalline, dark greyish rocks. Argillaceous or dolomitic bands are absent. Small cherty aggregates are the chief impurities mentioned. The limestone remains only as irregular residues in the midst of the wide-spread intrusive rocks which have penetrated the region.

The mineralization is confined to a belt extending 12 miles or so in a north-northwest direction, but seldom over one mile in width. The ore-bodies, which are exceedingly irregular in distribution follow a series of limestone inclusions in the igneous rocks. The metamorphic silicates and

the sulphides are developed both in the limestone and in the granite. The contact silicates are even more abundant in the granite than in the limestone, and in many places the contact between the two rocks is completely obliterated. From the descriptions and from the relations shown on McConnell's map, the rich sulphide ores apparently end abruptly against recrystallized limestone on one side, and pass gradually into contact-altered limestone or granite on the other. The distribution of the ores offersmany striking examples of the occurrence of sulphides between limestone and rocks rich in contact minerals.

The principal ore-minerals are magnetite, hematite, bornite and chalcopyrite. Other minerals of less common occurrence are arsenopyrite, tetrahedrite, galena, sphalerite, molybdenite, and chalcocite . Gold and silver occur in some quantity in most of the deposits. Pyrite is found in scattered grains in the granite but rarely occurs in connection with the ores.

The important contact-silicates mentioned by McConnell are garnet (andradite), augite, tremolite, actinolite, epidote, calcite, clinochlore, scapolite, serpentine and quartz. To these may be added from the study of other material, wollastonite , and diopside

According to Stutzer,[1] the succession is pyroxene-magnetite-garnet-calcite-sulphides. The bornite is clearly

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1. Zeitschr. f. prakt. Geol., 17, 1909, pp. 116-120. Lindgren, Mineral Deposits, New York, 1913, p. 668.

later than garnet or pyroxene, and probably later than epidote in material studied microscopically in the collections available. Calcite, however, is deposited in part at least later than the sulphides.

In the ores rich in iron, the bornite and chalcopyrite occur both in scattered blebs in the magnetite, apparently of contemporaneous age, and as bands and patches between the magnetite grains in the rôle of a cementing material. The most intense development of the copper sulphides was clearly later than the magnetite. The bornite and chalcopyrite are associated with mutual boundaries, and in a broad way they are probably contemporaneous.

Malachite, azurite, cuprite, tenorite and chrysocolla are present in the oxidized ores. Limonite is also common. The ores rich in magnetite are little altered at the surface. The sulphides in the rocks rich in contact silicates are usually resistant to oxidation, but in the limestone the alteration to oxidized minerals may be fairly complete to a depth of 100 feet. A small amount of chalcocite is developed as a replacement of bornite, and to a less extent, as a replacement of chalcopyrite. Covellite occurs but it is uncommon.

Summary. The bornite ores of the Whitehorse district are of distinct contact-metamorphic origin. The bornite and the associated chalcopyrite were formed later than

the intense phases of the mineralizationwhich produced the high-temperature silicates, (garnet and pyroxene). The sulphide ore-bodies are situated for the most part between intensely altered limestone and marmorized but otherwise unaltered limestone. There is noteworthy oxidation and a slight development of chalcocite apparently related to the present surface, which is significant, for the severe climatic conditions which prevail in this region at present, and have prevailed in the recent geological past, are not favorable for superficial changes.

THE MARBLE BAY MINE, TEXADA ISLAND, B. C.

INTRODUCTION.

The ore at the Marble Bay Mine, Texada Island, consists of irregular bodies of sulphides, apparently formed by the replacement of limestone in the neighborhood of small intrusions of dioritic rocks. The contact-metamorphic character of the deposit is clearly shown by the geologic relations, and especially by the nature of the accompanying rock alteration. Chalcopyrite and bornite are the chief ore-minerals, with garnet, diopside, epidote, vesuvianite and wollastonite abundantly developed in the adjacent limestone.

Situation. Texada Island lies in the Gulf of Georgia about fifty miles northwest of the city of Vancouver. The island is about 30 miles in length, and averages roughly 3 miles in width. The Marble Bay Mine is situated at an elevation of 55 ft. near the port of Vananda at the northern end of the island.

Development. There are several deposits in the neighborhood of Vananda which have been worked in an intermittant way for a number of years, but with the exception of the Marble Bay Mine, the irregularity in form and distribution of the ore-bodies has made the results distinctly discouraging. In the Marble Bay Mine, however, much larger masses of sulphides have been encountered with depth than would have been expected from the scanty surface showings, and until the last few years the annual shipments have ranged from 12000 to 15000 tons of ore, varying from 3 to 11 percent copper with 1-5 oz.

of silver and .1 to .7 oz. of gold per ton.[1] The mine is opened by means of a shaft about 1300 ft. deep. The ore occurs in a zone of discontinuous irregular bodies pitching to the northwest, which carries them from the neighborhood of the shaft on the upper levels to several hundred feet to the north and west in the lower workings. The deepest level (July, 1916) is termed the 15th, and is about 1360 ft. below the collar of the shaft, and a little over 1300 ft.below sea-level

Literature. The most complete description of the geology and ore-deposits of Texada Island is a report by R. G. McConnell, published as a memoir of the Canadian Geological Survey. In it, previous work of the Survey by James Richardson,[2] G. M. Dawson,[3] and O. E. LeRoy[4] is summarized. The bornite ores of the island have also been described by W. M. Brewer in a general article on the subject of bornite-chalcopyrite deposits of the coast-region.[5] Le Roy's views of the ore-deposit at the Marble Bay Mine are published in a later article[6] as well as in the earlier survey report[4] (1906) and they are essentially the same as those expressed in greater detail in McConnell's memoir.[7]

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1. R. C. McConnell, Texada,Island B.C.,Memoir 58,C.G.S.,1914.
2. James Richardson, Ann. Report C.G.S.,1873-74, pp 99-100.
3. G.M. Dawson, (1885) Annual Report C.G.S.,Vol. II,pp.36-37-B.
4. O.E. LeRoy, Preliminary Report on a Portion of the Main Coast of B.C. and Adjacent Islands,C.G.S.,1909.
5. W. M. Brewer, Jour. Can. Mine. Inst.,Vol.X.
6. R. G. McConnell, Loc. cit.

GENERAL GEOLOGY [1]

A series of volcanics and interbedded limestones known as the Anderson Bay formation are the oldest rocks recognized on the island. They are overlain by crystalline limestones of Triassic age termed the Marble Bay formation, which is of distinct economic importance as it is the chief ore-bearer of the copper region. Both formations are broken by extensive intrusions of variable nature called porphyrites, which are the most widely distributed rocks of the island. These are in turn intruded by quartz diorite, diorite and diorite porphyry which are believed to be local manifestations of the great igneous invasion at the close of the Jurassic that formed the Coast Range batholith. The quartz diorite and diorite form small stocks, but are not known in larger bodies on the island. A number of small intrusions of the diorite occur near the Marble Bay Mine, and are clearly the source of the mineralization. Diorite porphry dikes, either as direct apophyses of the stocks, or more widely distributed, are very common. They are frequently encountered in the workings of the mine and apparently increase in abundance with depth. The mineralization is believed by McConnell to have followed the period of dike intrusion.

No record of igneous activity later than the Jurassic is found. In the Cretaceous, a series of conglomerates, sandstones

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1. Summarized from R. G. McConnell's Memoir.

and shales were formed, but only remnants remain in protected depressions. The Tertiary is entirely a period of degradation. At the time of maximum glaciation in the Pleistocene the island was completely covered by southeastwardly moving ice. During part of this period the island was submerged, and interglacial clays, sands and silts were deposited along its coast. Glacial deposits containing marine fossils have been found on the island at an altitude of 500 ft., and are believed to indicate a post-glacial uplift of that magnitude. Since the retreat of the ice, and the rise of the land, conditions have been stationary for a sufficient time to permit occasional wide rock beaches and low cliffs to have been cut in the resistant quartz diorite or limestone. The southern part of the island composed chiefly of porphyrites, has been left a region of notable relief, with peaks rising to a maximum elevation of 2892 ft., while the northern part, composed of the softer sediments, has been worn by the long continued erosion to a milder country of basins and rough seaward sloping plains.

ROCKS AND ORES AT THE MARBLE BAY MINE

Limestone. The Marble Bay limestone is an obscurely bedded rock, grey or white in color, and in places of sufficient purity to be of commercial value. In the vicinity of the ore-deposits, however, it becomes marmorized, and impure with various contact-metamorphic silicates. Near the mine, no trace of bedding can be detected in it, although in places there is a curious fine banding.

Porphyry. Three small stocks of rather basic diorite and diorite porphyry outcrop in the neighborhood of the mine. Numerous apophyses from these bodies are associated with the ore, and below the 13th level, masses of stock-like proportions are encountered by the mine workings. Microscopical examination of specimens from the 15th level, show the rock to be composed of andesine and hornblende phenocrysts in a microgranitic ground-mass of andesine with some oligoclase and orthoclase. The feldspar phenocrysts occur in sharply euhedral forms, and in many cases are strikingly zoned, ranging from cores as basic as medium labradorite to rims as acid as oligoclase. The hornblende is commonly in small prisms. Some dikes are distinctly darke due to a greater abundance of hornblende. A small amount of biotite occasionally accompanies the hornblende. Small crystals of apatite, a little titanite and some quartz are usually present as accessories. The igneous rocks are fairly fresh, but show a slight development of the contact-metamorphic minerals.

Sericite in the feldspars, and calcite and chlorite as replacements of the hornblende however are common, even when the rock is apparently fresh. In a few instances, the alteration of the dikes is intense and accompanied by the introduction of sulphides. In these cases chalcopyrite usually predominates; bornite is rare.

Alteration of the limestone. The development of garnet, diopside and vesuvianite in the limestone was the earliest phase of the mineralization. The exact age relationships of the minerals are difficult to decipher, but it is fairly probable that the vesuvianite was earliest, and the garnet and the diopside roughly contemporaneous. The vesuvianite is less abundant than the others, but it is prominent in certain parts of the ore, and occurs often in large well-formed prisms, set in a cement of the later sulphides. The garnet is the yellow-brown andradite, usually in granular masses, but in places well-crystallized in small rhombic dodecahedrons. The diopside is much finer in grain, and is usually observed megascopically only as dull green compact material, making up a notable part of the altered limestone. Under the microscope, it is commonly seen to be in small but in many cases, euhedral, crystals, readily identified by their pyroxene cleavage, or in very fine shapeless grains comprising the chief mass of the rock. It is probably of equal quantitative importance with the garnet, but as it is less easily recognized, the garnet appears far more abundant in the field. Large masses of coarse laths of wollastonite are occasionally found, and fine laths of the mineral are fairly common under the microscope. Tremolite occurs with it but it is much less abundant. The two minerals are closely associated with diopside and garnet, and are probably of an early age.

Epidote, chlorite, sericite, and quartz form a second group clearly later than the minerals just described, since they are found chiefly as replacements of the earlier products. With these later minerals, the sulphides seem most closely associated, although in part the ores follow them, for euhedral or corroded inclusions of even these gangue minerals have been observed in the bornite and chalcopyrite. The epidote for the most part is the colorless variety low in iron. It is optically both positive and negative, but still beyond the range of clinozoisite. It forms broad bands in the altered limestone, and in places clearly replaces the earlier garnet, and vesuvianite. Sericite and chlorite are not abundant, but occur as replacements of feldspars and hornblende in the porphyries, or as seams in the other metamorphic minerals. Both are abundant in certain bornite and chalcopyrite grains, usually near the margins. Quartz is uncommon but occurs in small amounts in various relationships. Calcite is abundant, both as recrystallized grains of the limestone and as veinlets and masses of replacement origin, developed at the expense of the contact minerals.

One of the most unusual features is the occurrence of the zeolites, heulandite and laumonite, in grains with calcite and metamorphic minerals, or as fine seams cutting all other constituents. Their total amount is quite small, but they seem fairly widely distributed. The laumonite was present in sufficient quantity in one specimen from a garnet zone on the 15th level to permit the identification in the thin section

to be checked by means of index liquids. Certain other minerals of low relief were observed which may be other zeolites, but a satisfactory determination was not possible on account of the small amount of material.

Ore Minerals. Chalcopyrite and bornite are the chief sulphides. From the impression gained underground, chalcopyrite is more abundant at present, but from descriptionsof the larger ore-bodies, now mined out, it is probable that bornite was the most important ore-mineral. There is a small amount of pyrite, but usually not in the bornite ores. The pyrite, in the few polished chips where it was observed, is the earliest sulphide. Galena, steinmannite, sphalerite, tetrahedrite, and klaprotholite all occur in subordinate amounts. A little pyrrhotite was reported near a dike on the 7th level,[1] but it has not been recognized elsewhere. None was observed under the microscope. Molybdenite occurs in small amounts from the cropping to the lowest levels. Its relation to the copper minerals was not detected. A few grains of a hard, somewhat pinkish mineral were observed under the microscope, but it could not be identified by microchemical means. Native silver is said to be common in various parts of the mine. It occurred most abundantly in the large ore-body above the 13th level. Native gold has been reported but it is very rare.

The chalcopyrite and bornite are intimately associated; their boundaries are commonly of the mutual type, but as usual

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1. R.C.McConnell. Loc. cit. p.51.

there is a little evidence that the bornite was slightly later, or at least continued to form longer and corroded the chalcopyrite. There are few definite bornite veinlets in the chalcopyrite, but more numerous tongues and embayments of bornite tend to surround and isolate chalcopyrite grains than the reverse, and in general the sequence is fairly clear. (Fig. 50) In a few instances, the relations between the two minerals suggest the graphic structure. Sphalerite in rather large grains is not uncommon. It seems contemporaneous with the chalcopyrite as some fine grained intergrowths of the two minerals were observed and it is slightly corroded by the bornite.

In addition to the forms just described small specks and spines of chalcopyrite occur in the bornite, in some cases in fine lines of small blebs apparently along the contacts of grains. Galena and tetrahedrite are also common in this relationship, but in addition both of these minerals form minute and intricate graphic structures with the bornite, which are most readily interpreted as contemporaneous intergrowths. Associated with the galena, and not readily distinguishable from it except chemically is the arsenical antimonial variety, steinmannite. It is abundant in galena from the 15th level.

The small amount of a mineral, somewhat doubtfully identified as klaprotholite[1] was observed in the bornite.

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1. Klaprotholite was first determined in copper ores by F.B. Laney in material from Butte. It has also been observed by A.F.Rogers in ores from several different localities.(see Econ.Geol. Vol.XI,p.585 On the polished surface the mineral in the Texada ores has a bright creamy,silver-white color, and is distinctly softer than the surrounding bornite. Its microchemical properties are as follows:- with dilute HNO_3, brownish black,persistant; with dilute or conc. H Cl, brown then black, rubs to a gray surface: with KCN, no re-

The mineral is in round or elongated blebs for the most part, but in a few instances its vein-like form makes it very probable that it is a replacement of the bornite. In some cases, it forms small irregular feathery masses along the margins of bornite areas. The specimens in which it was observed were from a large ore-body on the 10th level. (Fig. 49).

Secondary Sulphides. Chalcocite and covellite occur in very small amounts as deep as the 10th level. They are usually present only as veinlets of thread-like dimensions, but in one specimen noteworthy rims of chalcocite follow the edges of bornite grains. The bornite is the only sulphide in which the veinlets are at all prominent. Fuzzy rosettes of covellite penetrate the bornite from certain ragged patches of included gangue minerals, and are identical in form, and appearance with covellite known to have been found by descending processes. In the chalcorite rims, in the case mentioned above, there is a notable amount of the klaprotholite, in ragged lacy forms, partially altered to a dull, blue-gray product, which in turn is surrounded by the chalcocite. There is a distinct suggestion that the klaprotholite formed an intermittant rim about the bornite areas, and that it became included in the chalcocite which replaced the bornite. The chalcocite as far as observed does not develop the lattice structure with the bornite.

The ores on the upper levels have been worked out, and the stopes are not accessible, but there was said to be no marked zone of secondary ores or of complete oxidation. Primary sulphides occur within a few feet of the surface. On the other hand a small amount of azurite occurs with the chalcocite in bornite in a specimen said to have come from the 10th level. It replaces the bornite in small peculiarly angular patches and grains.

Although 1300 ft. below sea-level, the lower workings of the mine are quite dry. Surface waters enter the mine along an open fracture termed the Mud-slip, but except during exceptionally wet seasons, the flow is caught on the upper levels and pumped back.

DISCUSSION

Distribution and origin of the ore-bodies. The relations between the zones of altered limestone and the ore-bodies are complex, and difficult to state in a general way. There is, however, a distinct suggestion that the ores occur most commonly between garnetized limestone and pure recrystallized or marmorized limestone. This is shown by Mc.Connell's maps of the levels.[1] In many cases, however, the sulphides apparently occur in unaltered marble, but in most of these instances, garnetized rock would probably be found in contact with the ore on the sides below the section shown on the maps. From the promising results in similar occurrences studied by A. Locke and E. H. Perry,[2] and from the valuable generalizations

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1. Op. cit.
2. Oral communication.

by J. B. Umpleby[1] on the distribution of sulphides, garnetized limestone and unaltered limestone in deposits of this sort, it is very probable that a thorough study of the distribution of ores with respect to altered limestone would yield results of definite commercial value in directing further prospecting for new ore-bodies.

There seems to be little significance in the relations of the ore-bodies and the numerous dikes. Both are probably manifestations of the same igneous activity, but it seems probable that the ores are later, as the dikes themselves become mineralized and altered. They may have had a directing action on the mineralizing solutions however, which would be worthy of study. McConnell suggests that the emanations which produced the ores were derived from deeper portions of the magma and not directly from the rocks exposed at present. The rising solutions were probably directed to a certain extent by the limestone - prophyry contacts.

Mineral sequence. The sequence of the minerals of the deposit, based on evidence obtained by the microscope for the most part, is expressed graphically on page (167). The details of the grouping are of course only a rough approximation, but certain broad features may be regarded with certainty. The sulphides are without question later than the garnet, vesuvianite, diopside, wollastonite and tremolite, and are more

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1. Loc. cit., pp. 25-37.

nearly contemporaneous with the epidote, chlorite and sericite. The zeolites (laumontite and heulandite) and the calcite in part are later than the sulphides. The occurrence of the zeolites in association with high temperature contact - metamorphic minerals is interesting testimony of the change from intense conditions of temperature in the early stages of the mineralization to mild hydrothermal conditions toward the close.

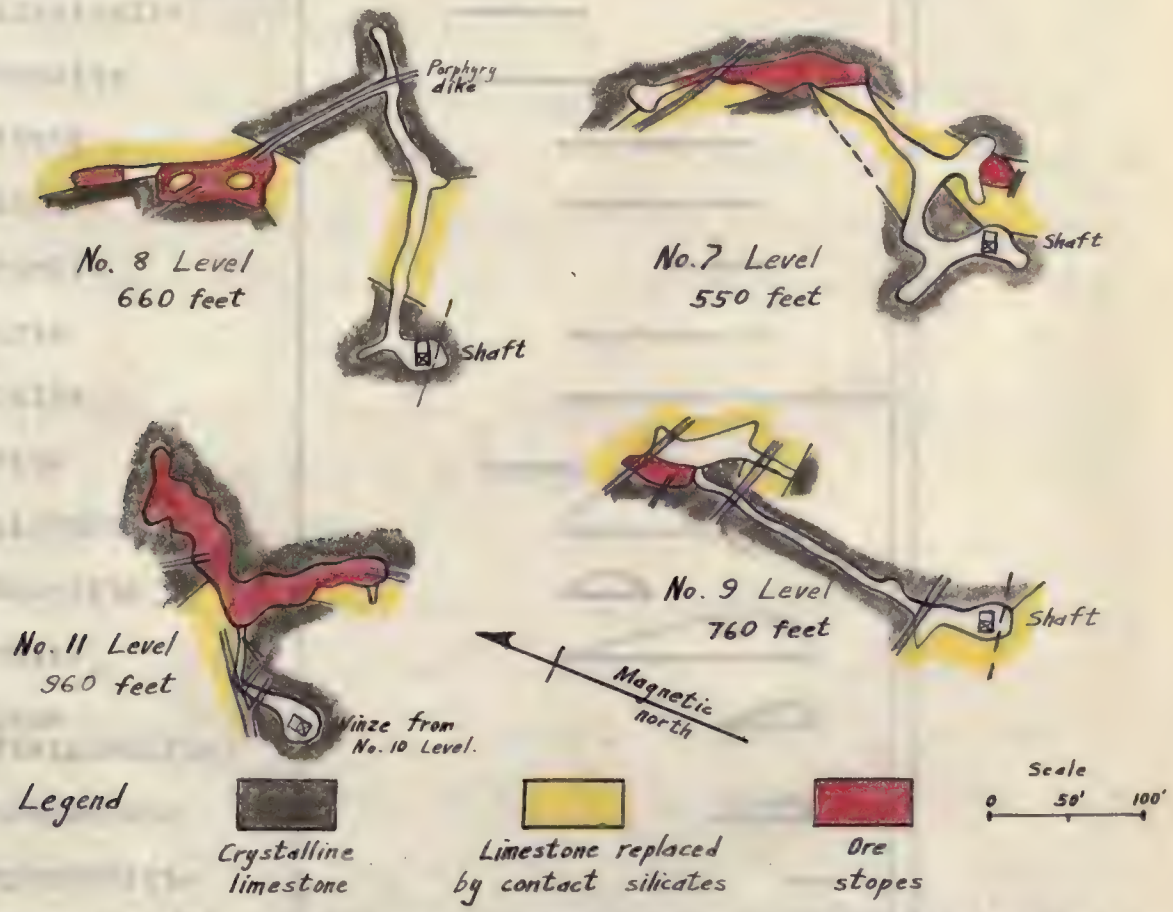

Fig. 10. Plans of ore-bodies on different levels of the Marble Bay Mine, Texada Island.[1]

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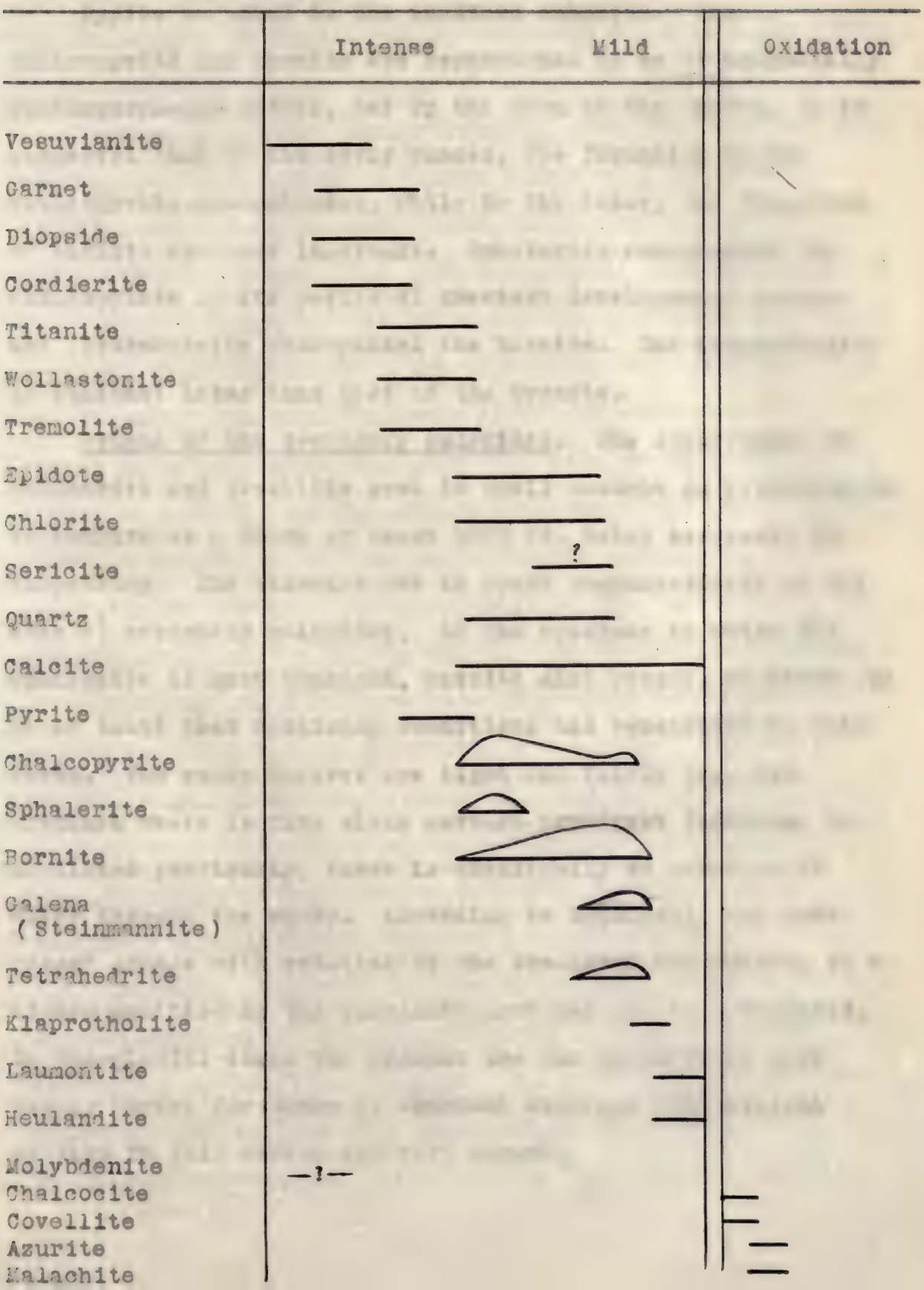
1. R. C. McConnell, Loc. cit.

Diagram of Mineral Sequence



Pyrite as usual is the earliest sulphide. The chalcopyrite and bornite are represented to be of essentially contemporaneous origin, but by the form of the curves, it is suggested that in the early phases, the formation of the chalcopyrite predominated, while in the later, the formation of bornite was more important. Sphalerite accompanied the chalcopyrite in its period of greatest development; galena and tetrahedrite accompanied the bornite. The klaprotholite is somewhat later than most of the bornite.

Origin of the secondary sulphides. The occurrences of chalcocite and covellite even in small amounts as replacements of bornite at a depth of about 1000 ft. below sea-level is surprising. The minerals are in forms characteristic of the zone of secondary sulphides. In the specimen in which the chalcocite is most abundant, azurite also occurs, so there can be no doubt that oxidizing conditions had penetrated to this depth. The rocks however are tight and fairly dry, and although there is flow along certain prominent fractures as mentioned previously, there is practically no movement of water through the rocks. According to McConnell, the most recent change with relation to the sea-level was uplift, so a higher position in the immediate past can not be postulated. In pre-glacial times the present ore was undoubtedly more deeply buried for there is abundant evidence that glacial erosion in this region was very severe.

Nevertheless in spite of these unfavorable conditions the chalcocite is there, and in forms which impel belief that it is secondary.

Waters may retain their oxidizing powers even after penetrating to great depths in barren limestone, for the rock contains few minerals susceptible to chemical alteration under oxidizing conditions. It is possible that slow lateral migration of waters of this sort may have produced the slight readjustments indicated by the chalcocite and covellite in the bornite. The azurite associated with the chalcocite may be formed by mildly oxidizing solutions rich in carbonate ions acting on bornite and the excess of copper from the reaction would be available for the production of chalcocite and covellite in cracks beyond the reach of the feeble oxidation. The tightness of the rocks, and the relation of the deposit to present and past sea-levels and to older topography are all unfavorable for the extension of secondary changes to notable depths. The occurrence of small amounts of azurite, chalcocite and covellite so deep below sea-level indicates the great ease with which the alteration of bornite to secondary sulphides takes place.

Summary. The ores of the Marble Bay Mine are of contact-metamorphic origin, and occur in limestone near intrusions of diorite porphyry. The sulphides replace the limestone and earlier high temperature silicates. They are closely associated with epidote, chlorite and sericite,

The rich ore bodies are usually situated between garnetized limestone on one side, and pure marmorized limestone on the other. The sulphides are believed to have been formed under conditions of intermediate intensity, milder than those which produced the garnet, vesuvianite and diopside, but more intense than those which produced the zeolites.

Bornite is the chief ore-mineral, but chalcopyrite is also abundant. The two minerals are closely associated for the most part but the bornite is slightly later. A mineral doubtfully identified as klaprotholite was observed as a replacement of bornite. Pyrite is practically absent in the ores in the altered limestone.

The great ease of the alteration of bornite to secondary sulphides is shown by the development of a small amount of chalcocite and covellite on the 10th. level, under conditions particularly unfavorable for deep enrichment.

Bisbee, Arizona.

The time has not been available either in the field or in the laboratory for as thorough a study of the complex problems connected with the Bisbee ore-deposits as has been given many of the other camps. The abundance of reliable information in accessible form,[1] however, makes it unnecessary to do more than merely outline the most important features related to the distribution of the bornite in the primary ores

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1. James Douglas, The Copper Queen Mine, Tran. A.I.M.E., Vol. 29, pp. 511-546, (1900).

F. L. Ransome; Copper deposits of Bisbee, Ariz., U.S.G.S., Bull. 213, 1903, pp. 149-157.
The geology and ore deposits of the Bisbee Quadrangle, Ariz., U.S.G.S., Prof. Paper 21, 1904.
Bisbee folio, U.S.G.S., No. 112, (1904).

Weed, W. H., The copper mines of the United States in 1905: U.S.G.S., Bull. 283, 1906, pp.99-100.

Arthur Notman, The Copper Queen Mines and Works, Part II, Trans. Inst. Mining and Metallurgy, Vol. 22, pp. 550-562, (1913).

W. L. Tovote, Bisbee, a geological sketch, Mining and Scientific Press, vol. 102, pp. 203-208, (Feb. 1911).

Y. S. Bonillas, J. B. Tenney and Leon Fouchère, Geology of the Warren Mining District, Trans. A.I.M.E, (Bull. 117, pp. 1397-1465; Sept. 1916). A detailed description of the ore-bodies, based on intimate knowledge of both the field and microscopic relations.

and the character of its alteration to chalcocite. My information of the field relations was gained largely from Messrs. Y. S. Bonillas and Leon Feuchère of the Copper Queen Co. and Mr. Ira Joralemon of the Calumet and Arizona Co. during the five days spent with them in the district.

Primary features of the bornite ores. Bornite is found in all parts of the Bisbee ores, but in general it is less abundant than chalcopyrite. In the disseminated ores of Sacramento Hill, however, chalcopyrite is lacking and the primary ore consists only of pyrite and bornite. The porphyry in which the bornite is associated is sericitized in general, and locally silicified. Elsewhere, as in the contact-metamorphic zone or in many of the ore-bodies in relatively unaltered limestone, chalcopyrite predominates although bornite is usually present. High temperature silicates such as garnet, diopside and wollastonite occur in the contact zone, but only in small amounts. The development of pyrite is believed to be later than these minerals, and closely associated with the sericitization of the porphyry and sediments, while the chalcopyrite and bornite are somewhat later and accompany the silicification. The relations indicate that chalcopyrite and bornite were produced under the same conditions, but that the formation of bornite lagged somewhat, and in part was a little later than the chalcopyrite. Sphalerite in small amounts is usually associated with chalcopyrite while galena is later and related more closely to the development of the bornite.

Secondary alteration. The distribution of oxidation and enrichment is well described and illustrated in the recent literature.[1] Oxidation and the development of chalcocite are deepest in the ores in little altered limestone, although in these cases an actual reduction of values per unit volume has taken place rather than an enrichment. In the sericitized porphyry ores, oxidation is slower and a distinct zone of sulphide enrichment is found. In the silicified contact breccia, where the ores are least permeable, the zone of oxidation and secondary sulphides is relatively thin.

According to Bonillas, Tenney and Feuchère,[2] the mine workings have now penetrated to a depth at which the rocks as well as the ores show no effects of surface changes, and continue downward without the vertical variations common in the upper portions. "Chalcocite is very abundant in many forms in the zone of enrichment but has not been seen in the undoubted primary zone, though this has been considerably explored." Consequently the geologists of the Copper Queen Company conclude that it is highly probable that the chalcocite was not formed by ascending solutions in this district. The force of this conclusion is slightly weakened by the fact that the zone of enrichment is so deep that primary variations in the ore could conceivably be confined to it. The greater abundance of galena on the upper levels offers an example of such a change, for this mineral is surely of primary origin.

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1. Y. S. Bonillas, J. B. Tenney, and Leon Feuchère. Loc. cit.

The chalcocite is to a large extent a replacement of bornite. The ratio of pyrite to chalcocite in many of the enriched ores is approximately the same as the ratio of pyrite to bornite in the primary ores, and there can be little doubt that in these the pyrite remained fairly resistant to the enriching processes. However, in some of the richer chalcocite ores, especially those mined some years ago, enrichment was sufficiently intense to have largely replaced the pyrite as well as the other sulphides. Chalcopyrite, as usual, alters less readily than the bornite, but in many parts of the ores it has been converted completely to chalcocite. Chalcocite has been observed associated with bornite in blebs in galena, which suggests that the latter is more resistant to chalcocite alteration than the former.

Microscopical study of the bornite-chalcocite ores, however, reveals a great variety of relations between the two minerals. In most cases veinlets or rims afford clear evidence that the chalcocite in part at least is of replacement origin. In such relations, the distribution of the chalcocite is clearly dependent on obvious channel-ways, such as the surface of contact between sulphide and gangue minerals, or along grain boundaries or definite fractures in the bornite. In the deeper ores, or in places where the development of chalcocite is less intense, the alteration of bornite yields the lattice-structure. In it all degrees of replacement are shown from the initial strips of chalcocite penetrating bornite fields to the final complete stages where bornite

remains only in bluish residues in broad areas of chalcocite. The triangular or rhombic pattern of the bornite chalcocite lattice is inherited by the chalcocite. It is shown either in the blue and white tints of the polished surface or by the etch-patterns developed with nitric acid or potassium cyanide. The white spines, which correspond to the first invasions of the chalcocite into the bornite etch more readily, while the blue areas between them are more resistant, and the lattice pattern is thus emphasized. Certain of the lines produced by etching, however, are not necessarily parallel to the lattice directions. The blue patches frequently etch with only one set of parallel lines, usually making a small angle to one of the directions of the lattice pattern.

The replacement origin of the chalcocite in the lattice-structure can not be doubted, but its attack on the bornite takes place in a selective manner which is difficult to explain. Certain grains or parts of grains may be largely reduced to rhombic or triangular residues of bornite between intersecting bands of chalcocite, while the adjacent bornite maintains a smooth resistant boundary against the corroding agents. The distribution of chalcocite in the lattice structure does not show the same dependence on obvious channelways for solutions such as grain boundaries and fractures that is commonly exhibited by secondary sulphides.

The graphic structure between bornite and chalcocite is only slightly developed in the Bisbee ores, but irregular

blebs and specks of bornite scattered through chalcocite fields often assume shapes very similar to it and are common. In modified form it has been observed associated with the lattice pattern, in relations which suggest that the chalcocite between the irregular bornite blebs was derived by replacement. Numerous small grains of bornite, with sharp clean outlines, often remain scattered through fields of chalcocite which are clearly products of lattice replacements. The distribution of these grains in many cases greatly resembles certain types of graphic patterns. The bornite grains are clearly isolated residues in chalcocite of replacement origin. It must be noted, however, that the lattice replacement in the final stages normally does not yield products of this sort, but sub-angular patches of bornite with hazy boundaries. The discussion of these significant relations will be postponed until the subject can be treated in a more general way on later pages.

Bornite residues or inclusions in chalcocite assume various peculiar forms. Bands of bornite near the margins of chalcocite areas are not uncommon. (Fig.). Spines of bornite remain apparently resistant in areas of well advanced lattice replacements. In other places, bornite occurs as a fine peppery sprinkling of sharply-defined specks in chalcocite. This association has been termed by J. Murdoch the "drop-emulsion structure," which is a very descriptive name,

but as the term "emulsion" suggests a contemporary origin for the two minerals, a less definite name, such as "drop-structure" is perhaps to be preferred.

Fine bornite stringers in coarse calcite veins have been observed almost completely replaced by chalcocite, which indicates that the enrichment of bornite to chalcocite is possible in the presence of calcium carbonate, and that the acid liberated by the reaction is not sufficient to corrode the limestone to any notable extent.

Secondary bornite is uncommon, although a small amount exists in the Bisbee ores. Fine veinlets of chalcocite cutting bornite areas have been observed to change into veinlets of bornite when chalcopyrite was encountered. Chalcopyrite residues in chalcocite in many cases possess complete or intermittent rims of bornite, which suggests that the alteration of chalcopyrite to chalcocite may take place through bornite. A more complete sequence is shown by successive rims of chalcopyrite and bornite, which may be termed "halos", around pyrite grains in a chalcocite field. The secondary origin of the bornite in these cases is probable, but the quantity of the mineral involved is very small. (Fig. 153).

Summary. The bornite at Bisbee is a replacement of porphyry or limestone under milder conditions than those under which the contact metamorphic silicates, the pyrite, or the sericite were developed. The bornite is accompanied by sil-

icification usually, but in some places replaces limestone without the development of other minerals. It occurs both in pyritic ores and in those poor in pyrite.

From the field evidence it is probable that the chalcocite associated with the bornite is all of secondary origin. The microscopical evidence indicates that the chalcocite is to a large extent a replacement of bornite. The chalcocite in the lattice structure apparently shows a selective action in its attack on the bornite, and there is evidence which suggests that the chalcocite-bornite graphic structure may be produced by a somewhat similar selective replacement.

DEPOSITS OF HYDROTHERMAL ORIGIN

The Magma Mine, Superior, Pinal Co., Arizona

INTRODUCTION

The Magma Mine is worthy of particular attention in connection with the study of the problems associated with bornite for a large percentage of its copper output is derived from this mineral. From a commercial standpoint, it is at present the most important bornite deposit in the United States, with the exception of certain ore-bodies at Butte and Bisbee.

Situation. The Pioneer Mining District of Pinal Co. is situated about 65 miles east of Phoenix, in the region of indefinite rugged ridges and peaks south of the Salt River. The chief town in the district is Superior, which is supported almost entirely by the Queen Mine of the Magma Copper Company. The actively producing camp of Ray is only 16 miles to the east, but across a rough ridge. A narrow gauge railroad extends to the south, connecting with the Arizona and Eastern Railroad near Florence. In addition to the railroad, an automobile stage service between Ray and Phoenix passes through Superior and makes the camp readily accessible.

The town of Superior is built on a gentle slope of

Appendix C (Supplementary Section)

The Rogue River Corridor Study Area, Oregon

Introduction

unconsolidated desert gravels on the northern side of an irregular structural valley, drained chiefly by Queen Creek. Immediately to the east, an imposing precipitous ridge known as Apache Leap rises about 1500 feet above the town, and presents to the geologist a fascinating section of the rocks of the district, exposed with almost diagramatic clearness. Queen Creek, which fringes the town on the south, breaks the escarpment with a deep gorge, along which the eastwardly dipping strata are cut in succession, as one ascends the stream.

Mines. The only ore-body in the vicinity of Superior which supports a mine of importance is property of the Magma Copper Company. The ore is almost entirely confined to a porphyry dike, which varies from a few feet to over 40 feet in width. It is worked by a 1500 foot shaft, and levels at the usual intervals. At the time of my visit, (August, 1916), the deepest workings were on the 1200 level, but since then the main cross cut from the shaft at a depth of 1500 feet has encountered the dike and found good bornite ore. The ores are rather complex, and in the deeper ore-bodies silver, lead and zinc values are sufficient to make their recovery worth while. Flotation has proved to be the most satisfactory method of concentration.

The Silver King Mine, five miles to the north, has been a famous silver producer in the past but it has not been in operation for many years. The ruins of the old mill, surrounded by crumbling adobe walls of the small town it

supported, may be seen from the Phoenix stage road, ten miles or so east of Superior, and still testify to the former greatness of the property. The Lake Superior and Arizona Mine, immediately north of the town of Superior possesses extensive drifts along the strike of the upper surface of the Cambrian(?) quartzite, but it has developed little ore.

Literature. Some notes on the geology and the ore-bodies of the district have been published by F. L. Ransome,[1] but no detailed paper has yet appeared. Earlier mine reports[2] furnish a little information, chiefly of value for the description of the older and now exhausted silver ores. An excellent topographic and geologic map of the ridges near the mine has been made by the engineers of the Magma Copper Co., but the work has not been published.

Acknowledgements. My thanks are due to Mr. W. C. Browning, the superintendent, for the privilege of visiting the mine, and for several rare specimens. A large part of my information concerning features of geological interest in the mine and in the immediate neighborhood was obtained from Mr. I. A. Ettlinger, the chief engineer, who very kindly devoted many hours to showing me all important parts of the deposit.

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1. Bulletin 540 D, U.S.G.S., Copper Deposits near Superior, Arizona, (1913).
2. One on the Silver King Mine, quoted by Ransome, is by W. P. Blake, Description of the Silver King Mine of Arizona, New Haven, 1882, 48 pp. with illustrations.

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PLATE V

Superior, Arizona.

Fig. 11. View to the south from the Magma Mine. Cambrian(?) quartzite outcrops on the lower slopes, with Carboniferous limestone above, capped by the great dacite cliffs of Apache Leap.

Fig. 12. Apache Leap from the west. The town of Superior at the base of the cliffs may be seen on the right. The deposit of the Magma Mine is situated along the fault shown by the displacement of the white limestone beds just to the left of centre.

PLATE VI

Superior, Arizona.

Fig. 13. The Magma Mine from the south.

Fig. 14. Outcrop of the Magma deposit. The prominent cropping in the foreground is quartzite.

General Geology

Sedimentary Column. The geologic column is exposed with satisfactory thoroughness on the bold cliffs of Apache Leap, and in the cañon dissecting it. The lowest of the sedimentary beds, and the oldest rocks exposed, are massive quartzites, averaging about 200 feet in thickness. They are of pre-Devonian age, and are probably to be correlated with the Cambrian(?) formations described in the neighboring Globe and Ray Districts.[1] The quartzite is overlain conformably by a thousand feet or more of limestone, ranging from Devonian into the Carboniferous. There are several well marked variations in the character of the limestone, which have enabled the local geologists to make seven or more subdivisions of the series.

Igneous Rocks. The igneous rocks noted are diabase, monzonite, porphyry, and dacite. The diabase forms large sills, the only one of importance at the mine being intruded into the quartzite. It is at least 1100 feet thick, as shown by the mine workings, and the floor has not been reached as yet. There are said to be exposures in the neighborhood, however, where the diabase sill may be seen resting on still lower quartzite beds, but the short time available did not allow me to see them. A few irregular trap dikes in the region are probably of the same general period

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1. F. L. Ransome, Some Paleozoic sections in Arizona and their correlations, Prof. Paper, 98-K, US. G.S., 1916.

of intrusion.

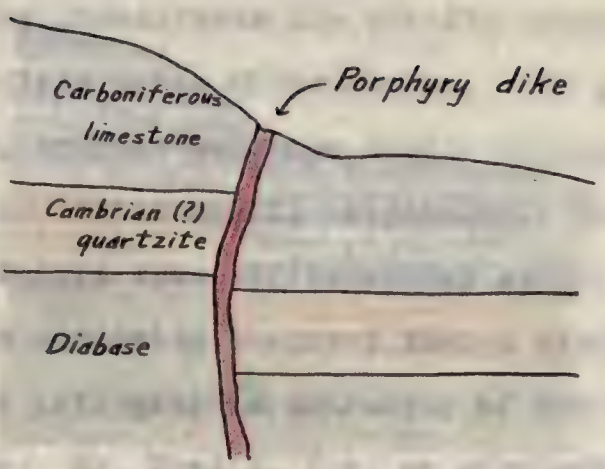


Fig 15A. North-south section through the Magma Mine.
Scale : 1in = 1000 ft.

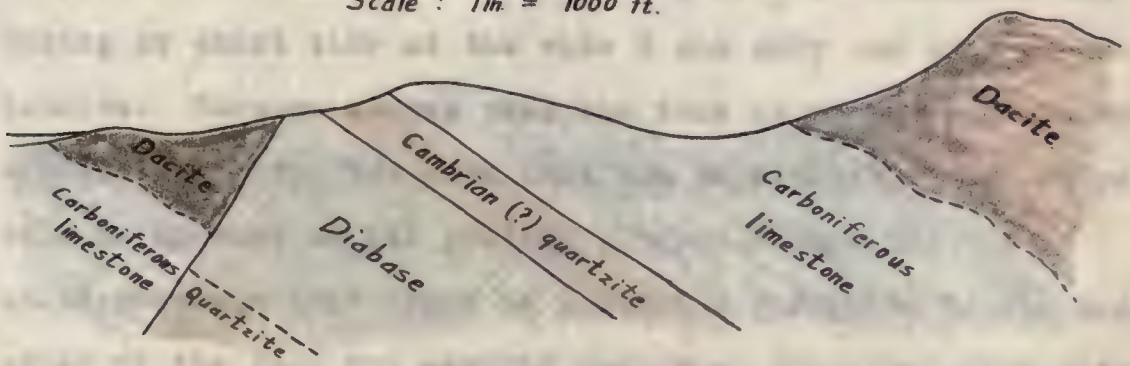


Figure.15B
West-east section through Apache Leap, near Magma Mine.

The porphyry, which is locally termed granite porphyry, occurs in a few dikes, the most important being the large dike in which the ores of the Queen Mine occur. The rock has a light gray color, with a slightly greenish tinge. Feldspar phenocrysts occur sparsely scattered in an aphanitic ground mass. Under the microscope, the original constituents in the specimens studied were found to be all greatly altered by the mineralizing processes, but the

original character of the rock may be reconstructed with little doubt. The phenocrysts are chiefly orthoclase, acid plagioclase, and thin laths of hornblende. The ground mass is microgranitic, and although now highly silicified it probably contained little quartz originally. The rock, as far as may be inferred from microscopical study, is more properly termed a monzonite porphyry than a granite porphyry. Variations in the petrographic character of the dike are said to occur, however. Mr. Fred B. Ely, an engineer of the company, believes that the dike is composite in character but during my short time at the mine I saw only one type of intrusive. Ransome states that the rock is probably a quartz diorite porphyry, but adds that the determination is not certain on account of its greatly altered condition. It is quite possible that there is a notable variation in the character of the rock but several specimens collected from different parts of the mine all indicate a monzonite composition for the chief mass of the dike.

The most prominent igneous rock in the vicinity of Superior is dacite, which occurs as thick flows resting on a fairly even erosional surface cut roughly parallel to the bedding of the Carboniferous limestone. The rock is of Tertiary age, and later than the dikes previously described. The Tertiary sediments which occur with the lavas in the Globe and Ray Districts are not exposed in the immediate vicinity of the mine. Coarse desert wash slightly cemented

fanglomerate, fills the valley to the south to an indefinite thickness, and nearly completely mantles the older rocks.

Structure. The sedimentary beds and the parallel igneous formations strike roughly north and south, and dip 30-40 to the east. The deformation is chiefly due to the faulting of post-dacite age. In the vicinity of Superior, the beds are broken by a strong north-south fault, which extends along the base of the steep eastern slope of Apache Leap. The boldness of the escarpment testifies to the

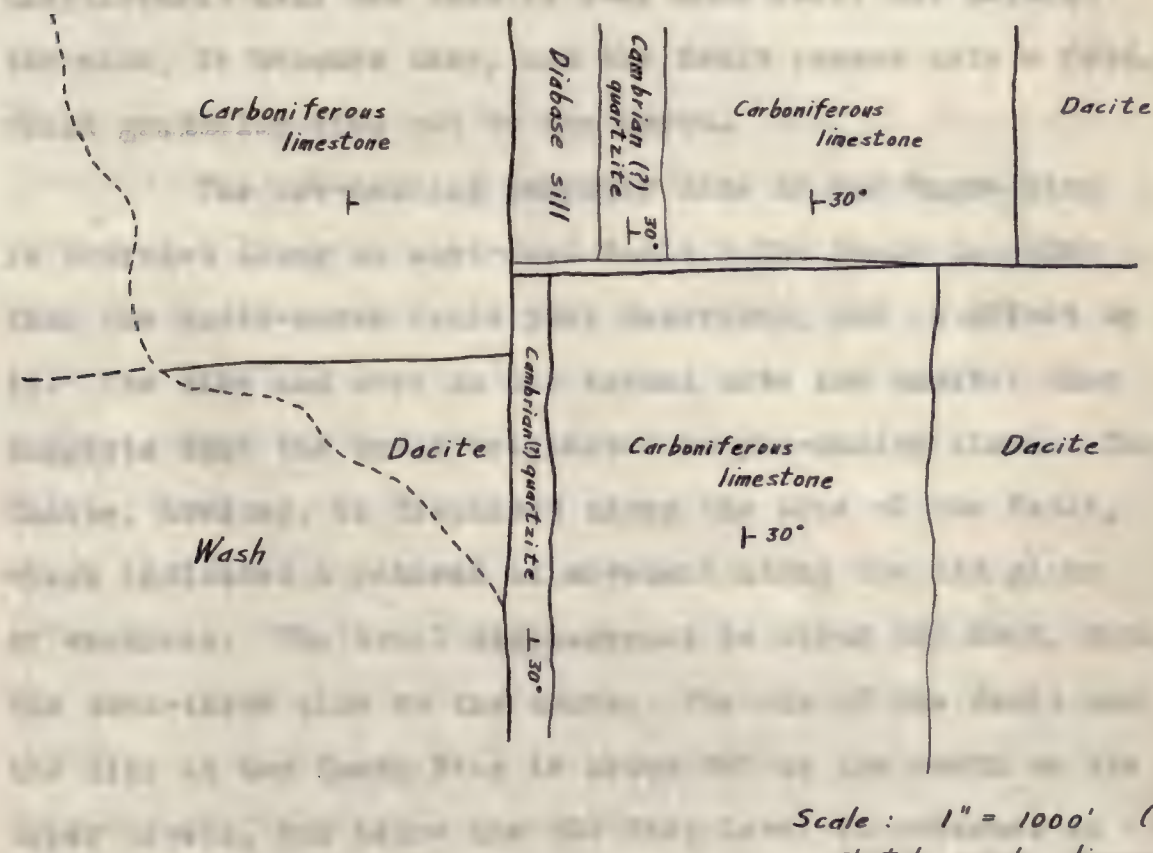


Figure 16.
Sketch map of geology near Superior, Arizona.

Figure 36.

youthfulness of the movement, and its height still approximately indicates the throw. Immediately to the west of the fault near the Queen Mine, dacite out-crops through the wash of the valley; to the east, the thick flows of dacite form the even crest of the ridge, and rise as a line of great splintery cliffs over 500 feet in height above the gentler slopes of the limestones. Near Superior, the actual break is concealed by the desert wash, but north of the mine, a spur of the ridge extends to the west of the fault, due to complications caused by cross fractures. The displacement near the town is over 1000 feet, but beyond the mine, it becomes less, and the fault passes into a fold, which gradually dies out to the north.

The ore-bearing porphyry dike at the Magma Mine is intruded along an east-west fault. The fault is older than the north-south fault just described, and is offset by it. The dike and ores do not extend into the dacite; this suggests that the break originated in pre-dacite times. The dacite, however, is displaced along the line of the fault, which indicates a renewal of movement along the old plane of weakness. The total displacement is about 800 feet, with the down-throw side to the south. The dip of the fault and the dike at the Queen Mine is about 70° to the north on the upper levels, but below the 900 feet level it reverses to to about 70-80° to the south.

There are several other smaller breaks, some of

which offset the ore slightly, but none are of any magnitude.

Primary Mineralization.

Form of Ore-Body. The ore at the Queen Mine, as has been mentioned previously, is largely confined to the porphyry dike intruded along of the east-west fault surface. The dike has a maximum width of 40-50 feet, but in places it pinches to a thin seam, or gives way entirely to a slickensided unmineralized fracture. The mineralization is most intense in the widest portions of the dike, and grows weaker where the dike becomes narrow. It usually ends many feet before the dike pinches completely. The sulphides occur in seams ranging from a fraction of an inch up to massive bodies several feet in thickness, or as disseminations in the porphyry. The former are by far the most important. One exception to the common relations between porphyry and ore is found on the 1200 level, where a drift to the south intersects a vein of pure chalcopyrite, one to two feet in width, which occurs in the wall rock many feet from the dike.

Distribution of Ore-Minerals. The distribution of the primary ores shows little dependence on the nature of the wall rocks. Ransome observed a tendency for the bornite ore-bodies to be richer along the contacts of the dike and quartzite beds, but subsequent development indicates that this relationship is not as important as it may have appeared at first. The mineralization along the dike is fair-

ly continuous, gradually dying out to the west, however, before the large north-south fault is intersected. In a broad way there seem to be two vertical zones of somewhat richer ore, one to the east of the shaft, the other slightly to the west of the shaft. In the neighborhood of the 500 feet level, very rich bodies of massive chalcocite occur in the eastern part of the ore-body which pass with depth into ore consisting predominently of bornite. On the same level, the western portion of the ledge contains rather lean pyritic material, which changes into rich bornite ores on the levels beneath.

Lead and zinc become of greater importance on the lower levels. Along one cross-cut on the 1100 feet level, the entire width of the dike is mineralized, and the assays along its wall show a notable banding of copper and of lead and zinc values parallel to the strike of the dike. A rich copper band follows the north side of the ledge (the high values being due chiefly to bornite). This changes sharply with little intermixing of the minerals into a band lean in copper and high in lead and zinc, which is in turn succeeded by another rich copper zone, with low lead and zinc values. The silver tends to rise with the copper, but it is also present with high assays of lead and zinc. Besides these variations in distribution of the metals across the ledge, there is said to be a distinct tendency for the copper to increase at the expense of the lead and zinc toward the west; toward the east the zinc increases with decreasing

copper values.

Mineral Sequence. The mineralization is clearly later than the crystallization of the porphyry, for its earliest products break the rock in seams, or replace its primary structures. Pyrite, as usual, was the first sulphide to form, and it occurs in large masses or scattered grains. It was accompanied by intense silicification of the ground mass of the porphyry, and by the replacement of the feldspar and hornblende phenocrysts by sericite. Both the pyrite bodies and the altered dike-rock offer abundant evidence of subsequent fracturing, which afforded channel ways for the following copper bearing phases of the mineralization. The pyrite is greatly shattered in places (Figures 93, 94), and the breaks emphasized and widened by bornite or chalcopyrite replacement. Veinlets of quartz carrying bornite or chalcopyrite, break the areas of earlier quartz and sericite. While it is possible that some of the copper minerals may have continued to form with the main mass of the bornite and chalcopyrite, the evidence of two stages, viz. one in which pyrite dominated, and the other in which bornite and chalcopyrite dominated, is very convincing.

Under the microscope the chalcopyrite and bornite may be seen to be in intimate association. For the most part, they exhibit mutual boundaries toward each other, but here and there the chalcopyrite is penetrated by imperfect veins of bornite, or grains of the chalcopyrite appear as if set

in a cement of bornite. The evidence is believed to indicate that here as at Engels, Evergreen, Marble Bay, and other camps, the two sulphides formed under the same conditions and at about the same time, but that the chalcopyrite slightly preceded the bornite. Under low magnification, however, fine lines of chalcopyrite appear in many specimens, apparently outlining bornite grains. (Figure 92). When examined more carefully, these lines are found to consist of irregular, somewhat elongated, disconnected blebs, and are not distinct, continuous veinlets. It suggests that, as the bornite crystallized, an excess of iron was concentrated or localized along the contacts of the grains, which resulted in the formation of the iron rich sulphide. In the diagram of mineral sequence, this idea is shown more clearly perhaps than it can be expressed here. In quantity bornite exceeds all other primary copper sulphides, and there is no reason to doubt that for the most part it is a direct replacement of the silicates or of the pyrite with which it is associated. The replacement of chalcopyrite by bornite was probably only a feeble process, for the evidence that it took place is not abundant, and the amount of bornite which originated in this way is without doubt relatively small.

Galena and sphalerite become of great importance in certain parts of the deposit, as may be inferred from the preceding paragraphs describing the distribution of the metals. They seem to be closely related in age to the bornite

and the chalcopyrite. The galena and bornite are associated in many cases, in structures similar to the graphic structure of bornite and chalcocite, although a greater variation in the size of the blebs is often shown. (Figures 89, 90). The sphalerite and chalcopyrite also occur in peculiarly intimate and fine grained structures which suggest an origin by contemporaneous intergrowth for the two minerals. In a few cases, bands of sphalerite were observed in bornite-chalcopyrite areas, but even in these relations there seemed to be a little corrosion of the sphalerite by the bornite. The relations usually exhibited by small areas of sphalerite surrounded by bornite offer little or no evidence concerning sequence. Where sphalerite and galena are abundant, the veins of the latter in the former, and the manner in which grains of sphalerite are surrounded and corroded by galena clearly indicate that the zinc sulphide was the earlier mineral. Elongated blebs of galena commonly occur in the lines of chalcopyrite blebs surrounding bornite grains, and seem of the same age as the chalcopyrite in this form. In general the sphalerite preceded the galena in time of formation and was probably a product of the same early conditions as those under which the larger part of the chalcopyrite was deposited. The galena became of importance a little later, probably associated with the abundant development of bornite, and continued to form with the later chalcopyrite in the fine fringes of small blebs about

the bornite grains.

The galena in part is the arsenical variety known as steinmannite. In physical properties it is identical with the ordinary mineral, but microchemical tests on the polished surface yield distinctive results. In some specimens, ordinary galena occurs alone or apparently intergrown with the arsenical variety.

Tetrahedrite is also fairly common with the ores. It is found chiefly in the bornite, as smooth grains, or as lines of elongated blebs, associated with the bands of chalcopyrite previously mentioned. In a few cases, it is fairly abundant and there is a little evidence that it is most common as a product of the closing portion of the bornite forming period. In one case, the tetrahedrite definitely cuts sphalerite, but its relations to the galena offer little evidence of their relative sequence. On the 1200 feet level, a silver-bearing seam is picked up by a long drift to the west, which extends well beyond the limits of the ore or the porphyry. The siliceous material of the seam occurs between walls of serpentinized diabase, and contains a little pyrite, spalerite, galena (and steinmannite), tetrahedrite, and native silver. The tetrahedrite is the most abundant, and probably contains the chief silver values. Native silver occurs also in the upper workings of the mine in oxidized ground, but the silver on the 1200 feet level has apparently no connection with superficial changes, and

is probably primary. (Cf. Marble Bay Mine, Texada Island, native silver on 1300 foot level, about 1200 feet below sea level).

Oxidation and Enrichment

Water Level. The original water level of the mine is stated by Ransome to have been about 400 feet below the surface, presumably at the shaft. While the ores above this level were almost completely of an oxidized character, the lower limits of oxidation are far deeper, and seem to have little relation to the present surface of the country or to the surface of the ground water.

Oxidized Ores. Below the 650 feet level, it is noticeable that oxidized products are encountered only in the eastern portions of the ledge. On the 650 foot level, the main drift to the west intersects a rather lean pyritic ore-body; on the same level, passing eastward, a rich cuprite, native copper and carbonate ore-body is encountered. On the 725 foot level, a lean sandy pyritic body is found to the west while to the east, oxidized and secondary sulphide ores become of importance. On the 800 foot level the oxidized ores occur again, but farther to the east than on the level above. The deepest oxidized material thus far encountered in the mine is found in the face of a long drift to the eastward on the 1300 foot level, which extends well under the dacite flows, that cover the Carbon-

iferous limestone. The relation of the bottom of the oxidation to the geologic structure is shown in the sketch below.

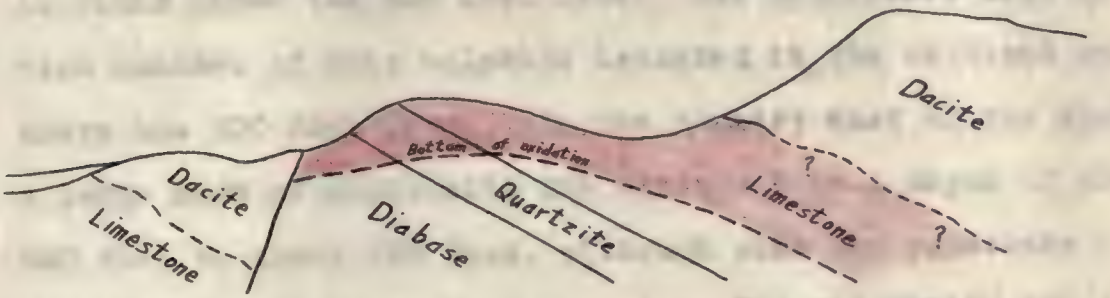
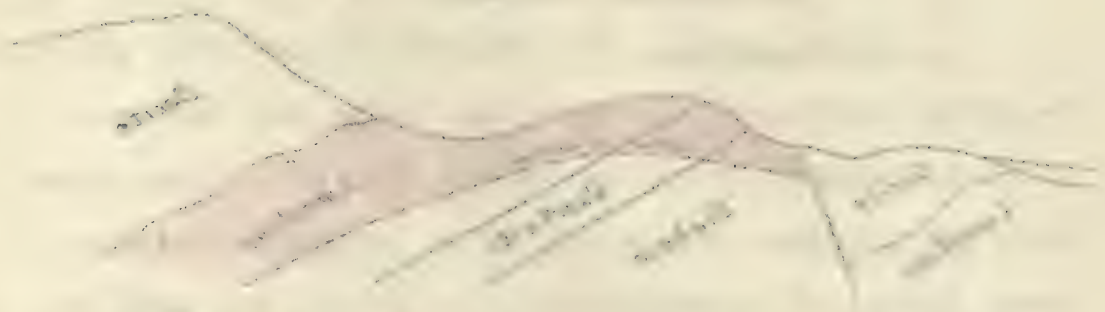


Fig. 17. Sketch Showing the Bottom of Oxidation and Its Relation to the Structure.

It may be mentioned here in passing that post-mine oxidation is intense in nearly all parts of the mine. The temperature and humidity are high, and in all except the most recent drifts, the wall rocks are decomposed and softened to a depth of several inches or more. The pre-mine character of the oxidation described in the preceding paragraph, however, is certain in each case, both from its lack of dependence on the walls of the drifts, and from descriptions given me by Mr. Ettlinger, who was familiar with the conditions when the drifts in question were first opened.

In the oxidized zone, cuprite is the chief copper mineral, but small amounts of malachite and azurite are commonly associated with it. Native copper and, rarely, native silver occur in small amounts both with the oxidized



minerals and in the chalcocite beneath.[1] Wulfenite occurs in small amounts in various places in the upper workings. Good crystals were obtained from the 650 foot level.

Secondary Sulphides. At present, little chalcocite is found above the 500 foot level, but old-timers tell of rich bunches of this sulphide isolated in the oxidized zone above the 300 foot level. In the country east of the shaft, a large body of chalcocite ore extends from a depth of about 500 feet to about 750 feet, although some may penetrate a little deeper, along fissures, etc. The underlying ore is rich in bornite, and there can be little doubt from the field relations, that the chalcocite is an enrichment product of the bornite, caused by descending meteoric waters. To the west of the shaft, the pyritic ore-bodies on the upper levels contain little chalcocite, and the underlying bodies of rich bornite ores contain it only as microscopic veinlets.

The microscope also furnishes evidence that the rich chalcocite ores were formed by a replacement of bornite. In certain chips, bornite residues veined and rimmed by chalcocite furnish convincing proof. The polished surface of the massive chalcocite, when etched with dilute nitric acid or potassium cyanide, breaks into very fine irregular

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1. Compare; Chase Palmer and E. S. Bastin, The rôle of certain metallic minerals in precipitating silver and gold, T. A. I. M. E., Vol. 45; pp. 234-238, 1914.

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1. Thomas, Elmer [Some Use] T. S. Eliot, The Pile of Vertical Material: Obstacle to Creativity, Wire Wire T. S. E. J. M. C., Pic. 18) pp. 334-338, 1918.

grains, about .01 mm. in diameter (Figure 97). The etch-structure of the individual grains usually possesses one set of strong parallel cracks, or less commonly two sets of different intensity and persistance roughly at right angles which is characteristic of orthorhombic chalcocite. The size of grain of the chalcocite indicated in this way is identical with the grain of the pure bornite from the deeper levels, revealed by etching and tarnish, and was undoubtedly inherited from it.

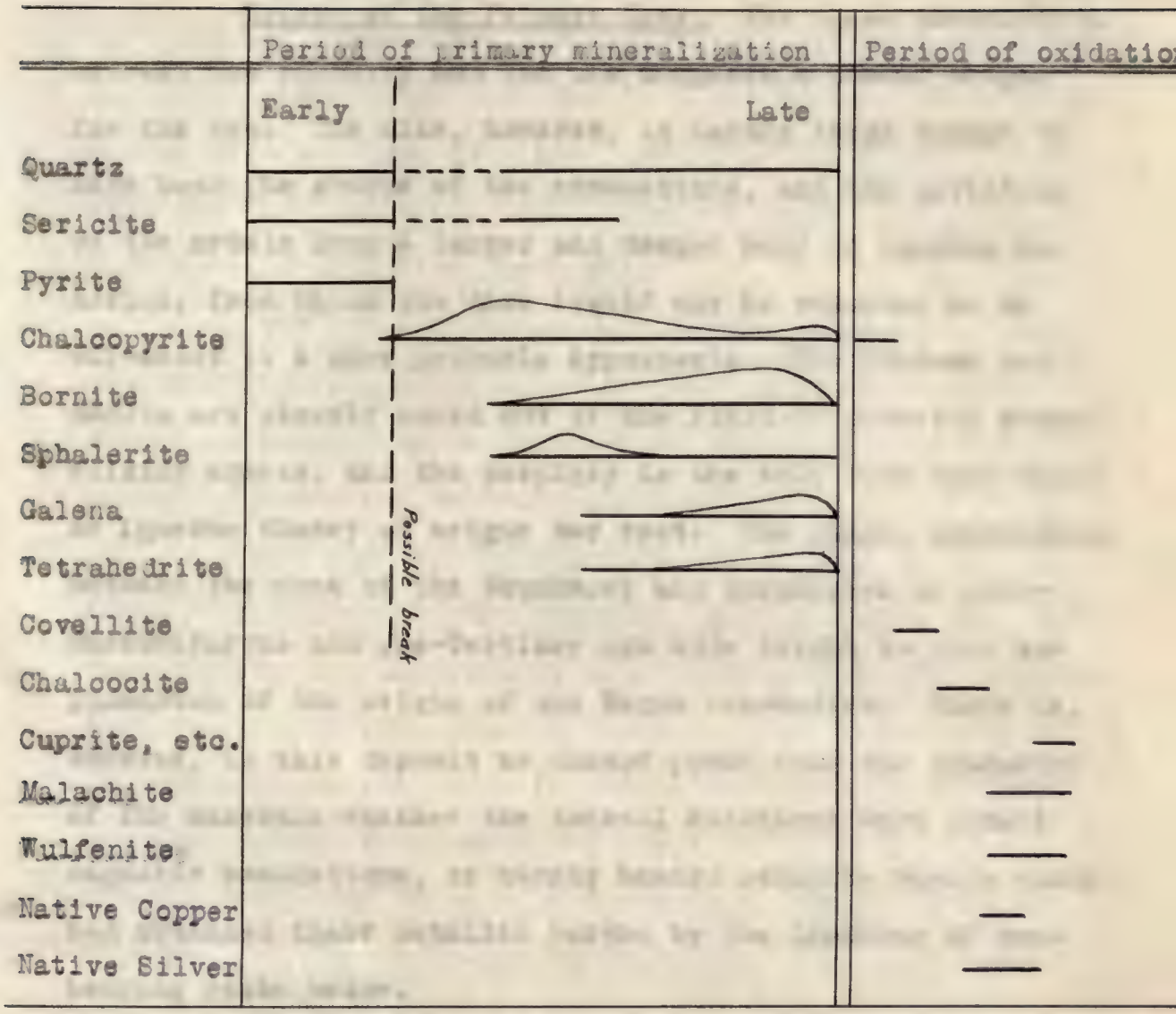
Covellite, in small amounts, is even more widely distributed than the chalcocite. It occurs as a sparse scattering of laths in some of the most massive glance of the upper levels, and thread-like veinlets of it, almost sub-microscopic in size, break the bornite in the deepest parts of the ore. Blunt laths of covellite are irregularly scattered or distributed in indefinite bands in the steely chalcocite from the ore-body immediately below the 500 feet level. The covellite is slightly attacked by the chalcocite, but the amount of replacement it has suffered is probably unimportant. Where the relations with the earlier sulphides may be detected, it is clearly shown that the covellite is almost entirely a replacement of bornite. Veinlets, which are merely fine threads in chalcopyrite or tetrahedrite, widen into broad bands composed of rosette-like sheaves of small covellite plates when they pass into bornite. In a specimen from the 725 foot level, veinlets of bornite, large-

ly altered to covellite but still containing residues of the original mineral, cut pyrite, chalcopyrite and the gangue minerals. The sharp confinement of the covellite to the limits of the veinlets clearly indicates the greater resistance of the other minerals to the attack of secondary solution.

The alteration of bornite to covellite is probably the result of the first weak effects of enriching surface solutions, and many of the covellite grains in the massive chalcocite, although probably not all, may have originally developed in the bornite, which was subsequently replaced by the chalcocite. A second generation of covellite, formed as the first stages of the oxidation of chalcocite, was not observed in the Magma ores, although it is a common feature in several other deposits studied.

Small spines of chalcopyrite occur sparingly in the bornite, associated with the faint blue covellite veinlets, and are probably of secondary origin. They form a very small fraction of the total amount of chalcopyrite in the ore, however.

DIAGRAM OF MINERAL SEQUENCE



Discussion and Summary

Origin of the Primary Ores. The close association between the porphyry and the ore suggests a common origin for the two. The dike, however, is hardly large enough to have been the source of the emmanations, and the deviation of the metals from a larger and deeper body of igneous material, from which the dike itself may be regarded as an off-shoot is a more probable hypothesis. The diabase and dacite are clearly ruled out of the field of possible mineralizing agents, and the porphyry is the only rock upon which an igneous theory of origin may rest. The common association between the ores of the Southwest and porphyries of post-Carboniferous and pre-Tertiary age adds weight to this explanation of the origin of the Magma ore-bodies. There is, however, in this deposit no direct proof from the character of the minerals whether the thermal solutions were direct magmatic emmanations, or merely heated meteoric waters which had obtained their metallic burden by the leaching of ore-bearing rocks below.

The ores are now at least a thousand feet below the Tertiary erosional top of the Carboniferous limestone preserved under the dacite, and this may be regarded as the minimum depth at which they could have been formed. In the neighboring Ray district, there is a thousand feet or so of Cretaceous volcanic material overlying the Carboniferous,

Circulation and Commerce

Effects of the Library Tax. The first qualitative
increase in circulation was the one occurring a decade before
the tax. The claim, however, is hardly large enough to
have been the result of the newspaper and book distribu-
ti the public Free Library had merely put an end to figures mer
relief. Even after the tax limit may be regarded as
effective in a more literal application. The decrease and
nearly ten thousand items out of the limit of possible advance
circul somehow, not the property is the only town open citizen
to Library Library at weight may well. The reading association
between the case of the Secretary and population of Pitts-
Institutions and corporately sub main weight is also ex-
pendents at the origin of the Eugen corporations. Under is,
however, in its beyond or other great time the observer
of the original figures the thereof relations rate direct
magnetic associations, in merely newest networks meters effi-
but withdrawn their monthly notice by the taxation of pre-
berring rents below.

The same may now at least a shoreline that within
the Thirteen population its of the Corporations investors
presented under the Bailey, not also not be figured as the
station light at which they still have been focused. In the
mitigation her letter, which is a tendency that we be of
tremendous returns economic sensitive the Continuation,

but it is not known whether it extended over the country as far west as Superior or whether it is older than the porphyry. The ores are undoubtedly later than the post-Carboniferous porphyry, and earlier than the Tertiary dacite, but a closer dating does not seem possible. Probably it is safe to assume that the ores now mined were formed at depths not greater than three or four thousand feet.

The geologic relations and the character of the accompanying rock alteration indicate that the deposit should be classified as an ore-body formed at moderate depths by ascending thermal solutions.

The pyrite, chalcopyrite, except the spines associated with covellite, bornite, galena, sphalerite and tetrahedrite are all clearly of primary or hypogene origin. There is a distinct sequence shown by their relations, which is indicated in the diagram, but it is believed that they were all formed from ascending solutions. The pyrite is clearly broken by veins of both chalcopyrite and bornite (Fig. 95) and the chalcopyrite is for the most part somewhat earlier than the bornite.

From the relations exposed at the time of his visit, Ransome expresses the opinion that the bornite is of secondary or supergene origin, although he frankly states that the evidence is inconclusive. The ore was exposed to a depth of 800 feet at that time, and there seemed evidence that the richest bornite ores occurred in

two shoots each related to the two zones of contact of the dike and the displaced quartzite stratum. This relation Ransome believed to be most easily explained as a result of descending surface solutions, which had derived their copper both from the ledge above and from lenses of copper-bearing sulphides near the base of the Devonian limestone, similar to those which occur at this horizon in the neighboring Lake Superior and Arizona Mine. The mingling of solutions descending along the dike with solutions migrating along the quartzite which is the chief water carrier of the sedimentary series is suggested by Ransome as the probable cause for the localization of the bornite at the contact of the porphyry and quartzite. The bornite is regarded by him as a replacement of chalcopyrite, on evidence similar to that presented on the preceding pages, and it is recognized that the chalcocite is largely a replacement of bornite. These relations are believed by Ransome to indicate that the bornite is the first and deepest product of secondary enrichment (supergene alteration), and is an intermediate step in the change of chalcopyrite to chalcocite.

Later developments indicate that the bornite continues without notable change in relative abundance to the deepest levels (1500 feet) and does not pass into lean pyrite-chalcopyrite ores with depth as the hypothesis of a secondary origin would demand. The ore-shoots parallel

to the quartzite horizons proved to be less definite than the first exposures had indicated, and the distribution of the bornite in general shows little relationship to the structure of the sediments.

At Magma, as elsewhere, bornite is found to be more susceptible than the chalcopyrite to chalcocite enrichment which is shown by the marked manner in which the chalcocite is confined to the bornite where both minerals are present. In a few cases, thin margins of bornite were observed aroun chalcopyrite residues in chalcocite, and it is possible that this small amount of bornite may represent an intermediate product in the enrichment of chalcopyrite to chalcocite. But even here, it is not certainly the case, for the bornite rims themselves may be residues, perhaps protected a little longer than usual by the concentration of iron derived from the chalcopyrite, or possibly by some galvanic action.

The association of bornite and galena in structures which can be interpreted only as contemporaneous intergrowths or as replacements of bornite by galena is strong evidence that the bornite is not derived from descending solutions, for secondary galena is unknown in copper ores. The same argument may be made in the case of the bornite and tetrahedrite, based on similar relationships.

In summary, the persistence of the bornite with depth, its relation to galena and tetrahedrite, and the lack

of dependence on present or past land surfaces or on the structure of the sediments, all indicate with a high degree of certainty that the rich bornite ores of the Magma Mine are of primary (hypogene) origin. The replacement of chalcopyrite and gangue by the bornite is regarded as a primary process, similar to the replacement of pyrite by chalcopyrite.

The Origin of the Secondary Ores. The chalcocite may be regarded without question as a product of descending solutions. Microscopical evidence, supporting the field relations, indicates that it is chiefly a replacement of bornite. No graphic structures between bornite and chalcocite were observed in the ore. In some cases the attack of the chalcocite developed a pattern not unlike the "ice-cake structure" described by C. F. Tolman, Jr.[1] In one specimen, a tarnish on the polished surface revealed coarse bornite grains apparently set in a cement of finer grains. Where chalcocite was developed, the finer grained matrix was attacked, but the larger grains apparently remained resistent. In advanced stages of chalcocite replacement, they appeared as islands surrounded by broad streams of chalcocite, in which floated numerous small residues of the finer grains. The advance of the chalcocite is probably directed merely by physical causes, such as the greater surface offered by the finer

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1. C. F. Tolman, Jr, Observations on certain types of chalcocite and their characteristic etch patterns, T.A.I.M.E., Vol. 54; pp. 402-435, 1917.

material, and not by any variation in the nature of the bornite.

The distribution of the chalcocite agrees with the distribution of the oxidation; i.e. it seems related to a surface dipping to the east parallel to the bedding, as has been described. This may be attributed to two causes, both of which undoubtedly were of importance, (1) the influence of the different strata on the penetration of oxidizing solutions, and (2) the existence of a land surface of low relief in pre-dacite times. They will be considered in order.

The limestones and quartzite are both pervious rocks, and rocks in which it is commonly observed that surface changes easily penetrate to considerable depth. (Tintic, Bisbee, Bingham.) The thick diabase sill which forms the wall rock of the dike below the sediments is rendered dense and impervious by the abundant development of serpentine and uralite, and offers a serious check to descending waters. The diabase out-crops in a band a couple of hundred feet in width north of the ledge, and dips into the ridge at an angle of about 30° parallel to the overlying sediments. It does not out-crop on the southern side of the ledge, but its position and relations are indicated clearly on the mine sections. (Figures 15A and 15B). The greater depth of oxidation to the east may be attributed to the increasing depth of the sediments in that direction, and to the barrier

offered by the diabase rising to the west. It should be kept in mind, however, that the slope of the present surface rises to the east, and that the distance of the lower limits of oxidation below the surface increase more rapidly than indicated by the quoted depths below the collar of the shaft.

From the physiographic side, there are two surfaces of importance in connection with the secondary ores, viz., the pre-dacite surface and the present surface. From the strikingly even line shown by the contact between the dark lava and the white underlying limestone, it is clearly seen that the dacite flows were poured out over a country of low relief, in this neighborhood at least. The underlying limestone beds had been little disturbed in pre-dacite time, and conditions of slow erosion with accompanying deep oxidation undoubtedly prevailed. This period was brought to a close by the floods of lava. Superficial changes of the ore were thus checked, until the faulting and subsequent erosion which broke the monotonous plains of dacite, again exposed them. The recent surface is still one of steep and almost precipitous slopes. Mechanical erosion is probably the dominant process by which the escarpment is retreating at present, and its rapidity is unfavorable for the production of deep oxidation. Of the two surfaces, the older seems more competent to have been the one to which the present deep oxidation is related. This conclusion is further supported by the rough parallelism between the bottom of the

oxidized zone, and the limestone-dacite contact.

There is no reason to doubt that part of the oxidized and secondary ore was formed in relation to the pre-dacite surface, and on the whole, it is very probable that the greater part of the rich chalcocite bodies were formed at that time. While it is true that enrichment can keep ahead of a rapidly retreating surface, as at Bingham cañon, it is extremely doubtful if the massive and deep chalcocite in these large ore-bodies, which represent a very complete replacement of the primary sulphides, could have been formed so rapidly. From the structure of the ridge and the high country to the east, it is probable that the sill of diabase would tend to act as a dam, retaining water above its level in the mountain rather than allowing it to migrate down its upper surface. As there is abundant water in the mine at present the sediments were, without doubt, well saturated below a depth of 500 feet before the mine was opened. Any flow of the ground water under the present structural conditions would tend to take place from the higher country east of the mine toward the valley, which would force the water up the beds and through the diabase at the lowest outlets. The present climate is extremely arid, and there is no reason to assume a depressed water level due to less humid conditions in the past. The height of the mine above the valley wash eliminates the possibility that the present higher level of the ground water is caused by the accumulation of detritus.

From the various lines of evidence a depth of about 500 feet below the shaft may be set as the lower limit to which intensive oxidation can extend from the present surface, and it is believed that the deep oxidized ores and the chalcocite are most probably products of enrichment related to the pre-dacite surface, which is now tilted to the east at an angle of about 30° . Studies by other members of the staff of the Secondary Enrichment Investigation afford impressive evidence that the main period of oxidation and enrichment in the neighboring Globe and Miami region was earlier than the dacite and the subsequent tilting, which greatly strengthens the similar interpretation in the case of the Magma deposit.

Conclusion. The results of this study indicate that the rich bornite and chalcopyrite ores of the Magma Mine are of hydrothermal origin, and formed slightly later than the post-Carboniferous porphyries but earlier than the Tertiary lavas. The bornite is a replacement of pyrite and chalcopyrite in part, but it is not a product of descending solutions, except to an almost negligible extent. The rich chalcocite ore-bodies were formed largely by the replacement of the primary bornite, and are a product of descending surface solutions chiefly in pre-dacite time.

THE OCCURRENCE AND SIGNIFICANCE

OF

BORNITE

by

Donald Hamilton McLaughlin

VOL. II

KENNECOTT, ALASKA.

INTRODUCTION.

The ores of the Kennecott district are predominately chalcocite. In them, bornite attains only a low rank on a quantitative basis, but it assumes a position of especial interest due to the critical evidence it presents on certain questions of genesis. The secondary or primary nature of the chalcocite ore-bodies offers an important problem, and its solution depends to a large extent upon the meaning of the bornite residues in the ore and upon the interpretation of various structures of the chalcocite and bornite.

In addition to the great chalcocite bodies, which are confined to a limestone formation, bornite ores occur in many places in the district in a thick pile of altered basic lavas known as the Nikolai greenstone. They are similar in many respects to the general type of ores associated with basic lavas in many parts of the world, and afford an instructive contrast to the chalcocite ores. Both classes of deposits have passed through a similar history in geologically recent times, which provides a common ground upon which their different reactions to the processes of surficial alteration may be compared.

Situation. Kennecott is situated at about 61° 30' north latitude and 143° west longitude on the lower spurs of the southern slopes of the great Wrangell Range in southwestern Alaska. The camp is at an altitude of about 2000 ft. on the

ELECTRICITY. FLAMES.

INTRODUCTION.

eastern side of the broad Kennecott glacier, which descends from the ice-fields of Mt. Blackburn, (16140 ft.) only 23 miles to the northwest. The Kennecott River, which springs from the end of the glacier five miles south of the camp, drains into the Nizina River which soon joins the Chitina, a broad stream flowing westward sixty miles or so through a wide structural depression to the Copper River, whose deep glaciated valley penetrating the Chugach Range affords an outlet to the Pacific for the waters of the entire region. The Copper River and Northwestern railroad extends from Cordova on Prince William Sound to Kennecott, a distance of 196 miles by way of the canons of the Copper River and the Chitina Valley, and makes the camp at all seasons of the year.
accessible
A

Mines. The Bonanza and the Jumbo Mines, which are worked by the Kennecott Copper Corporation, are in all respects the most important properties in the region. They are situated high on Bonanza Ridge, a spur extending to the south from the lofty Wrangell Range. Bonanza Peak, the highest part of the ridge, rises to an altitude of 6950 ft., which is about 4500 ft. above the Kennecott glacier to the west, and the narrow valley of McCarthy Creek to the east. The mines are less than 600 ft. from the crest, and in an extremely rugged topography due to the intersecting cirques of small mountain glaciers. The mill and other works are situated at the ter-

minus of the railroad at Kennecott at an elevation of 2017 ft. The ore is transported to the mill by aerial tram-ways, which are also used for carrying supplies and members of the staff up to the mines. The Erie Mine, which lies about four miles north of Kennecott and about 1000 ft. above the glacier, has been developed to a slight extent by the company, but as yet little ore has been shipped.

On the eastern side of Bonanza Ridge, and about a half mile to the east of the Bonanza Mine, is the Mother Lode Mine, the property of a smaller company. A fair amount of development work had been done in 1915, an aerial tram-way built to McCarthy Creek, and some ore had already been shipped.

All of the deposits at the mines mentioned thus far are in the Chitistone limestone, and the ore is to a very large extent, chalcocite. There are, however, in the vicinity of Kennott numerous small deposits of copper minerals in the Nikolai greenstone, but little work has been done on any of them. To the east, on Nikolai Creek, a deposit of this sort has been slightly developed, with results somewhat promising. Many miles to the west, in the Kuskulana and Kotsina Districts, several similar deposits in the greenstone have been worked in a small way, and from a mine on Nugget Creek, the property of the Alaska Development Co., a little ore has been shipped. Our work at Kennecott did not allow time to visit these distant deposits, but specimens and descriptions have been kindly furnished by Mr. Alfred Wandtke,

Literature. The region has been mapped and described in a very thorough and useful manner by the United States Geological Survey. Their most recent and valuable publication for local information is Bulletin 448, The Geology and Mineral Resources of the Nizina District, Alaska, by F. H. Moffit and S. R. Capps. (1911). The accompanying topographic and geologic maps were found to be of great benefit for all questions within the limits of accuracy of their scale, (1/62500). When the Survey work was done, however, the mines were only slightly developed, and consequently the published descriptions of the ore-deposits were of little value to us. A list of earlier papers which have contributed to the knowledge of the region is given in Bulletin 448 and is appended below.[1] A private geologic report by Professor J.D. Irving gave valuable information and data on the large ore

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1. Allen, Lieut, H. T., Report of an expedition to the Copper, Tanana, and Koyukuk rivers, in the territory of Alaska, in the year 1885, Washington Gov. Printing Office, 1887.

Hayes, C. Willard,. An expedition through the Yukon district: Nat. Geog. Mag., Vol. 4, 1892, pp. 119-162.

Rohn, Oscar, A reconnaisaance of the Chitina River and Skolai Mountains: Twenty-first Ann. Report., U.S.G.S., pt.2, 1900, pp. 393-440.

Schrader, F.C., and Spencer, A.C., The geology and mineral resources of a portion of the Copper River district, Alaska: Special publication of the U.S.G.S., 1901.

Mendenhall, W. C., and Schrader, F. C., The mineral resources of the Mt. Wrangell district, Alaska: Prof. Paper, U.S.G.S., No. 15, 1903.

Mendenhall, W. C., Geology of the central Copper River region, Alaska, Prof. Paper, U.S.G.S., No. 41, 1905.

Moffitt, F.H. and Maldren, A.G., The mineral resources of the Kotsina and Chitina valleys, Copper River region, Bull., U.S.G.S., No. 345, 1908, pp. 127-175.

Keller, H. A., The Copper River district, Alaska, Eng. and Min. Jour., Vol. 85, No. 26, June 1908, pp. 1273-1278.

Moffit, F. H., and Maddern, A.C., The Kotsina-Chitina region, Alaska: Bull., U.S.G.S., No. 374, 1909.

bodies mined during the first few years of the life of the Bonanza Mine.

The "isometric cleavage" of the chalcocite from the Bonanza Mine was first described by Graton and Murdoch[1], and its similarity to the structure of synthetic chalcocite, formed at a temperature of 1100°, was regarded as an indication of the primary origin of the mineral. The presence of bornite residues in the chalcocite and the possibility that it was derived from the bornite by replacement was, however, mentioned later by L. C. Graton.[2] Analyses and specific gravity determinations of chalcocite from the Bonanza Mine made in the Geophysical Laboratory at Washington have been published by Posnjak, Allen and Merwin[3], and from their results, it was concluded that the mineral was formed at a temperature above 91°. From the results of a microscopical study of a suite of specimens from the Bonanza Mine[4], C. F. Tolman, Jr., concluded that the "isometric structure" of the Bonanza chalcocite was inherited from bornite, and that the greater part of the chalcocite of the deposit was a replacement of bornite. A statement of the paragenesis of the ore-minerals is made, but, as the results are based largely on laboratory studies without field work, several of his conclusions may be criticised.

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1. The Sulphide Ores of Copper, T.A.I.M.E., Vol. 45, p. 768, (1913).
2. Discussion, T.A.I.M.E., Vol. 48, 1915. p. 199.
3. The Sulphides of Copper, (Secondary Enrichment Investigation, Contribution No. 3), Econ. Geol., Vol. 10, pp.491-535.
4. Observations on Certain Types of Chalcocite and their Characteristic Etch Patterns, T.A.I.M.E., Vol.54, 1916; pp. 402-441.

Excellent photographs of polished surfaces of the Bonanza ores, accompany the article, and clearly illustrate certain structures and relations of the ore-minerals.

Acknowledgements. Our work was greatly assisted by generous information and many courtesies from Mr. H. W. Seagrave, the manager of the properties at Kennecott, Mr. H. D. Smith, superintendent of the Bonanza and Jumbo Mines, and Mr. W. E. Dunkle, examining engineer and geologist for the company. Excellent geologic maps of the mines, prepared by Messrs. Smith and Dunkle were of great value in facilitating ou observations.

Many of the ideas concerning the field relations of the ores that are presented on the following pages I owe to L. C. Graton and to Dr. A. M. Bateman, but the intricate way in which they are woven into the entire fabric prevents specific recognition in the text, and allows me merely to express at this place my appreciation of their advice and valuable criticism.

GENERAL GEOLOGY.

Nikolai Greenstone. The base of the visible geologic column near Kennecott and in the entire district, is the Nikolai greenstone. The formation, as exposed on the slopes of Bonanza Ridge, consists of a thickness of a little over 3000 ft. of altered basaltic flows. The base is not recognized, as the lower boundary is due to faulting for the most

part, and consequently its local thickness may be considerably greater. The formation is wide spread, extending in an irregular belt beyond the Nizina River to the east, and with interruptions into the basin of the Kotsina River to the west. From several good exposures, Moffit and Capps consider it highly probable that the formation has a maximum thickness of over 4000 ft.

When viewed from a peak near the mines, the formation is seen to be distinctly stratified in rather thick beds probably representing individual flows. (Figures 19, 21). Close measurements were not possible, but no flows were recognized thinner than 30 ft. A change from a dense, fine grained rock to a reddish amygdaloidal type was observed at many horizons, and is probably the expression of the variation from the bottom to the top of an individual flow. The dense rock is a fairly fresh gray lava with a fine-grained diabasic texture; the amygdaloidal rocks are commonly much more altered, and are of a dull green or red color. All gradations exist between the two extremes. Cliffs are frequent along the horizons of the denser types, while the reddish rocks seem to weather preferably to benches.

From a microscopic study of many specimens, the fresh rock is known to consist of laths of plagioclase, (basic andesine for the most part), with grains of colorless augite, characteristically in the ophitic texture. Magnetite is accessory, and a small amount of chalcopyrite and rarely other copper minerals is found. The subordinate ground-mass may have been glassy, but none was seen in an unaltered state. The alter-

ation of the lavas is widespread, and even in the freshest specimens, there is a slight development of secondary materials. The ground mass has in all cases gone to radial aggregates of pennine and delessite. In most specimens, the pyroxenes are partially or wholly altered. Serpentine is also present, but its separation from chlorite in many cases is very difficult. The feldspar is more resistant, but in the most intensely altered types, it passes into an aggregate of chlorite and calcite, with more or less kaolin.

Zeolites are uncommon near Kennecott, but a small amount of epistilbite was observed in one section, probably as a replacement of feldspar. In material from Elliott Creek in the Kotsina District, heulandite occurs in a similar relation, and datolite is abundant in small albite-bearing veins. Moffit[1] reports thomsonite in a specimen from Chititu Creek and A. Knopf[2] describes zeolites in the lavas of the White River country. The amygdule fillings are largely calcite, with some quartz, and chlorites. Bornite, chalcopyrite, and pyrite occur in the amygdules in various mineralized zones, and in a few cases native copper was observed. The relations of these minerals will be discussed more fully under the descriptions of the mineralization in the greenstone. In a few places, the weathering out of the amygdules has resulted in

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1. Bull. 448, U.S.G.S., p. 61.
2. The Copper-bearing Amygdaloids of the White River Region, Alaska, Econ. Geol., Vol. 5, pp. 247-256.

a vesicular rock with a striking resemblance to a recent lava.

The greenstone under normal conditions of erosion would tend to yield rather smooth forms, but under the severe attack of the tributary glaciers near Kennecott, the upper slopes of the ridges are precipitous, although the cliffs are usually not as bold as the overlying massive beds of limestone. The rock gives rise to a rich, brownish-red soil, which supports a luxuriant growth of grasses and shrubs, and spruce on the lower levels.

The age of the greenstone is definitely limited in one direction by the overlying Triassic limestone, but the lower limit is uncertain. On account of the similarity between the Nikolai greenstone, and post-Carboniferous volcanics in the Skolai Pass country to the northeast, Moffit and Capps[1] consider it probable that the formation is of early Triassic age.

Chitistone Limestone. The Nikolai greenstone is overlain by a sedimentary formation known as the Chitistone limestone. In a broad way the contact appears conformable, the well defined beds of the limestone being parallel to the somewhat less distinct flows of the greenstone. (Figs.19,34). However, where mining operations have exposed the relations more clearly, and in a few other cases, there is evidence of movement along or not far above the contact. The movement was probably a thrust, but in general it is not of sufficient importance to mask the essentially conformable character of

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1. Loc. cit., p. 63.

the two formations.

The surface of the old volcanic rocks on which the Chitistone formation was laid down appears to have been practically flat, perhaps with slight irregularities here and there, but with no notable relief.

The first deposit consisted of about three feet of mud, now consolidated to purplish red or dull greenish shales. Near Kennecott the shale is a persistent bed, and encountered along the contact for many miles. It tends to yield a bench, by its weathering, which forms the easiest line of travel in several regions of difficult cliffs. (See Fig.34c).

The shale is succeeded by about thirty feet of an impure silicious limestone, made up to a notable extent of flattened cylindrical bodies suggesting fossils. Numerous fragments of crinoid stems were found in this horizon. Above these beds occur 40-50 feet of grey limestone. The rock has a dull appearance on the freshly fractured surface due to its very fine grain, and it is commonly known to the miners as the "dead limestone". The chief part of the formation, which overlies this type of rock, is a crystalline dolomitic limestone. It is separated from the gray limestone by a sharp boundary parallel to the bedding for the most part but not infrequently breaking across in irregular ways. Numerous analyses made by Mr. Dunkle have shown the change in crystalline character of the limestone to be closely associated with the change in magnesia content. The fine-grained limestone

is fairly pure, yielding 9.30 % $CaCO_3$ with 3.9 $MgCO_3$, while the dolomitic rock averages about 66.7% $CaCO_3$ and 30.5 % $MgCO_3$.

The Chitistone limestone is estimated to have a thickness of about 3000 ft. It passes without any noticeable break into shales, so it is difficult to place the upper limit closely. The upper beds of limestone become more and more impure, shale partings become more frequent, until finally the true lime character of the formation is lost, and the rock becomes a distinct shale.

The McCarthy Shale. This upper formation, which may have a thickness in the neighborhood of 3000 ft., has been termed the McCarthy shale. The shale is entirely removed by erosion from Bonanza Ridge, but it occurs to the east of ~~the~~ McCarthy Creek, where it is exposed to good advantage in an imposing 2000 ft. cliff. Fossil evidence has shown the limestones and shale to be of Upper Triassic age.

Post-Triassic Deformation. After the deposition of the McCarthy shale, a period of orogenic deformation occurred. The rocks near the mines were folded into a broad anticline with a NW-SE axis, and eroded to a surface of gentle relief. The erosion was sufficient to expose the underlying greenstone in many places, for the overlying sediments of the Jurassic rest on all three of the foregoing rock divisions.

Kennecott Formation. The McCarthy shale is succeeded unconformably by the Kennecott formation, a series of black shales, gray shales, cherts, sandstones and conglomerates,

which from its best exposures has been estimated to be at least 7000 ft. thick. It is known to be of Jurassic age, and rests on the even erosion surface cut across the greenstone, and the Triassic sediments.

Near Kennecott it occurs as a thin veneer of shales and cherts, resting on the greenstone, and preserved only in a few down-faulted patches. The section of Bonanza Ridge shown in Fig.18 illustrates the probable relations. In the cañon of National Creek, running up from the Kennecott Mill, a thickness of several hundred feet of cherts and shales is

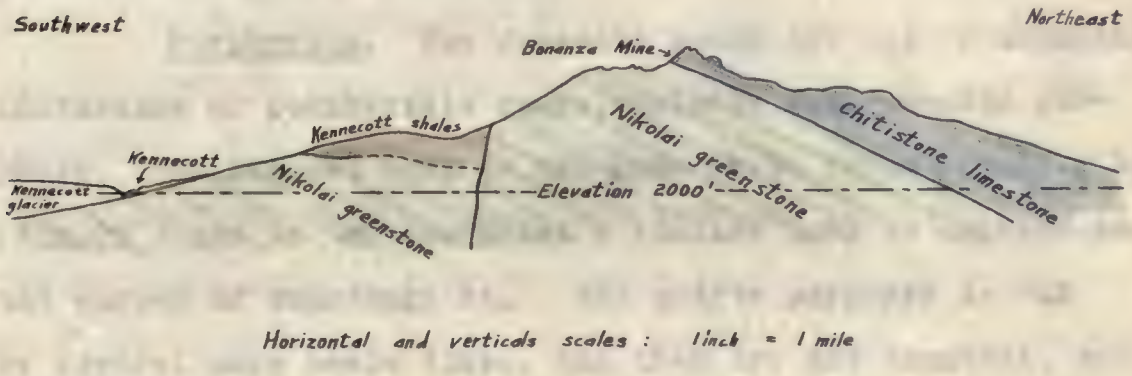

Fig.18. Section through the Bonanza Ridge near the Bonanza Mine.

exposed. The chert occurs in distinct beds 2-3 inches thick, separated by partings of shale, a fraction of an inch thick. This remarkable alternation of cherts and shales is almost identical with that found in the Franciscan series in California (Jurassic, radiolarian cherts)[1], and again in the Monterey series, (Miocene, diatomaceous cherts) (Fig.25). The significance of the rhythmical change has not been deduced as yet. The gray shales are exposed along the lower course of Bonanza Creek, but the black shales of the formation

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1. Hinde, G. J., Note on the radiolarian chert from Angel Island and from Buriburi Ridge: Calif. Univ. Dept. Geol. Bull., Vol. 1, No. 7, pp. 235-240; 1894. Also A. C. Lawson, The SanFrancisco Folio, U. S. G. S., (1915.)

Fig. 12. Section through the Devonian strata near Ben Bhreac.

were observed in this neighborhood only as inclusions in the porphyry of Porphyry Mt. Conglomerate boulders, probably of the Kennecott formation, were observed in the bed of National Creek, but the rock in place was not found. With the exception of a small pocket of sandstone probably of Eocene age west of the glacier, and the Quaternary gravels of the valleys, the Kennecott formation completes the sedimentary column near the mines.

Porphyries. The Jurassic rocks are cut by abundant intrusions of porphyritic rocks, chiefly white quartz porphyry. The largest body is the mass which forms Porphyry Mt., (Fig.22) and to the southeast a similar body is exposed on the slopes of Sourdough Mt. The quartz porphyry is cut by several more basic dikes, but they are not abundant, and are of very subordinate volume.

Under the microscope, the porphyry is seen to contain phenocrysts of quartz and plagioclase. The latter is commonly acid andesine, but it is as acid as oligoclase in some cases. Orthoclase phenocrysts are rare. Biotite occurs in small amounts, as short laths, usually greatly altered to muscovite; hornblende is the only other ferromagnesian mineral, and it is very subordinate and usually oxidized to limonite at the surface. The ground mass is micro-granitic, and is composed commonly of an interlocking mass of small quartz and orthoclase grains. Near the edges the rock has a glassy

ground mass, but even in the heart of the area, the grain is extremely fine. The rock is considered a quartz diorite porphyry by Moffit and Capps, from a wide study of its occurrences.

The bodies forming Porphyry and Sourdough Mts. are referred to by Moffit as laccoliths, but in no place was I able to see any evidence that they had made way for themselves by thrusting aside the older rocks. Both are apparently intrusions in the Kennecott shales. The beds along the edges of the porphyry exposed in the cañon of National Creek are intimately intruded by sills, but are not noticeably disturbed. The rock of Porphyry Mt. contains numerous inclusions of black shale, many of very irregular shapes, which stand out in striking contrast to the white porphyry host. (Figs. 24,26) The horizon of the black shale in this vicinity is not known, but a possible interpretation is that the inclusions are blocks which have settled from above in the course of magmatic stoping. The contacts of the porphyry and the shale zenoliths are sharp, and there is no evidence of assimilation. The irregular forms of some of the zenoliths must be attributed to mechanical causes rather than chemical. As the porphyry probably made its way upward into the Jurassic terrane by replacing the beds, and as there is no evidence of a floor, it is preferable to refer to these bodies as stocks rather than laccoliths.[1]

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1. See section AA' of the map accompanying Bulletin 448 for the form of the Sourdough Mt. "laccolith."

The fine grain of the rock is surprising in such large bodies. Porphyry Mt. stock is about five miles in the north-south diameter and about two miles in an east-west direction. The porphyry mass of Sourdough Mt., which I saw only from a distance, is about five miles in diameter in a southeast-northwest direction, and is probably continuous with the stock of Porphyry Mt. under the gravels of McCarthy Creek. From the distribution and dip of the Jurassic sediments near the western base of Porphyry Mt., it is clear that the cover over the intrusion could not have been thick even if the igneous rock did not penetrate far above its present positions. The fine grain is probably accounted for by this condition.

The porphyry intrusions are confined to the Kennecott formation to a surprisingly complete degree. Near Kennecott, only two porphyry bodies were observed in the older rocks; one a small dike cutting the Chitistone limestone at the Erie Mine, and the other an irregular patch of porphyry in the greenstone near the glacier about 2 1/2 miles above the mill. In all cases in this vicinity, the porphyry occurs as intrusions in the Jurassic sediments. This relation has been investigated with especial care by the members of the Survey, and it has been found to be usual throughout the entire district. The greater ease of injection of the magma into the fissile shales of the Kennecott formation than into the more massive older rocks is offered by Moffit and Capps as an explanation. The

confinement of the porphyries to these areas of well-bedded sediments, may mean that the intrusions were later than the deformation of the Jurassic rocks. The places, where the Jurassic sediments now occur, are mostly basins formed by faulting or folding, and the lower position of the fissile beds in these areas may have allowed them to offer the easiest pathway for the rising magma. If the porphyries were intruded before the floor beneath the Jurassic beds had been deformed, there is less reason for the remarkable absence of the intrusions in the underlying rocks which of course were penetrated. No upper age limit for the porphyries can be definitely set. They are not earlier than the late Jurassic, and are probably earlier than the Tertiary volcanics. They may possibly be phases of the great igneous activity at the close of the Jurassic, but there is no direct evidence to prove or disprove this view.

The Wrangell Volcanics. The lofty Wrangell Range to the north of Kennecott consists of a great series of lava flows and associated fragmental rocks, which range in age from the early Tertiary to the present day. (Figs.28,30,31). A summary of the evidence gathered from various portions of the range indicates that the volcanic activity probably commenced in the Eocene, but that the greater part of the lavas were

poured out later in the Tertiary and in the Pleistocene.[1] Andesitic flows from Mt. Wrangell interbedded with glacial debris are described by Moffit and Maddren,[2] and explosive eruptions of the mountain have occurred within the last few years. The volcanics are strikingly well bedded, and rest in nearly horizontal positions on a surface of low relief, now at an altitude between 6000 and 7000 ft. As seen from Bonanza Peak (Fig.31) they have a slight dip to the northwest. The upper portions of the range are buried in snow and ice, but there can be little doubt that the great peaks are of volcanic origin. Additions to Mt. Blackburn probably ceased a fairly long time ago, for the mountain is strongly eroded, but Mt. Wrangell to the west is still in an active period of growth, and appears as a rather flat cone, with smooth, little eroded sides.

Structures. The conformable greenstone and limestone formations, which are the chief rocks near the orebodies, strike northwest and dip about 25° in the vicinity of the Bonanza Mine. From the bold exposures on the cliffs, it is clearly shown that the dip increases slowly to the northwest, and on the western side of the Kennecott glacier it flattens to almost zero to the southwest. (Figs.28,29)

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1. Capps, S. R., The Chisana - White River District, Alaska, Bull. 630, U.S.G.S.,(1916), p. 61. (Good summary).
Mendenhall, Loc. cit., p. 57.
Schrader and Spencer, Loc. cit., p. 52.

2. Bull. 374, U.S.G.S.,(1909), p. 42.

The beds apparently form the northern limb of a broad anticline with a northwest-southeast axis. The structure is interrupted on the south by the porphyry intrusions and a fault which has dropped the Jurassic beds against the limestone.

Near the Bonanza Mine, a variation in the strike N 15° W to N 45° W indicates the existence of a small cross fold, with an axis pitching with the dip to the northeast.

There is clear evidence in the mine workings and elsewhere of movement along a surface roughly parallel to the bedding about 50-60 ft. above the greenstone-limestone contact. The magnitude of the slip along this surface, which is commonly referred to as the "flat fault" is not known. In places it is accompanied by a strong zone of brecciated rock and gouge. On the cliffs of the sharp peak which rises between the Kennecott Glacier and its tributary from Mt. Regal, there is evidence of thrust faulting parallel to the contact. (Fig. 28). The limestone beds are

locally overturned, and a broad wedge of the limestone seems driven into the underlying greenstone. The structure is complicated, but from a study with the field glasses, we felt that it afforded good evidence of compression in the limestone parallel to the greenstone contact. From this condition west of the glacier, it is probable that the "flat fault" at the mines is a reverse fault, although there is no evidence of any folding of the beds on the eastern side of the glacier.

The limestone-greenstone contact is a strikingly bold feature, due to the sharp contrast in color of the two rocks, (see Figs.19,20,29,34), and its course may be followed for many miles along the bare upper slopes and steep cliffs. The line is remarkably regular, but in a few places it is broken by cross-faults. South of the Bonanza- Mine, a fault has dropped the block on the southern side about 300 ft. (Fig. 20), and on a spur south of the Jumbo Mine, there is a similar fault with about the same throw. All other breaks observed were of small displacement.

PHYSIOGRAPHY

The land surfaces which may be recognized as important stages in the geological history of the district are five in number. They are as follows:

(1) The surface of the greenstones on which the Chitistone formation was deposited;

(2) The surface cut across the disturbed greenstone and Triassic beds, upon which the Jurassic sediments were laid down;

(3) The Tertiary surface on which the Wrangell volcanics were poured out;

(4) The pre-glacial surface; and

(5) The present surface.

Pre-Chitistone Surface. - The great pile of lavas represented by the greenstones was little disturbed or eroded before the overlying shales and limestone of the Chitistone formation were deposited. It has been urged that the evenly distributed amygdules and the concordance of the flows and the sediments indicate a submarine origin for the volcanic rocks.[1] From the sections along which I studied the greenstones, however, I found a distinct confinement of the amygdules to definite horizons, which were with little doubt the surfaces of the individual flows. Limonitic alteration is far more pro-

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1 - J. D. Irving, Private report to the Kennecott Copper Corporation.

nounced in such portions of the rock, and is strong evidence of a subaerial origin. According to this interpretation, the upper surface of the greenstones was once a land area.

Pre-Kennecott Surface. - The surface upon which the Jurassic sediments were deposited is the first of importance in possible relation to the secondary alteration of the great ore-bodies in the limestone. Near Kennecott there are few opportunities to study the character of this surface in detail, but as the Jurassic shales and cherts rest on the greenstone(Fig.18) it is evident that a period of profound erosion preceded their deposition. Elsewhere in the general region, the lower beds of the Kennecott formation have been seen resting on the evenly truncated edges of both the greenstone and Triassic formations.[1] Erosion of the pre-Jurassic structures had clearly advanced well toward peneplaination before the Jurassic sediments were deposited.

Pre-Volcanic Surface. - The next land area of which there is a definite record is that preserved beneath the Tertiary volcanics which form the higher altitudes of the Wrangell mountains. Seen from Bonanza Peak, the contact of the flat lying lavas and the earlier formations presents a strikingly even line. (Figs.30 and 31). The surface truncates the older beds, and

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1 - Moffitt, F. H. and Capps, S. R., Bull.448, U.S.G.S., Plate VII, opp. page 36.

represents a land area of very slight relief. Toward the western end of the Wrangell group, however, Mendenhall describes irregularities as great as 3,000 feet vertically in this pre-volcanic surface,[1,2] but for the most part, descriptions and photographs from neighboring districts[3] show it to be similar to the conditions observed north of Kennecott. The pre-volcanic surface most probably extended over the Kennecott region, about a thousand feet at least above the highest peaks east of the mines, if its present low dip may be projected. The lavas extend south on Bonanza Ridge to a point within six miles of the mines, but it is not known whether they ever continued much farther south. Areas of flat or gently rolling country at altitudes between 5,500 and 6,500 feet were observed on ridges west of the Kennecott glacier (Fig. 29), south of the Chitina Valley, east of the Nizina River and elsewhere, and they may represent remnants of this pre-volcanic early-Tertiary surface, which was not buried by the lavas. It is possible, however, that these surfaces may

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1 - Loc. cit., pp 56 - 57.

2 - Shrader, F. C. and Spencer, A.C., The Geol. and Min. Resources of a portion of the Copper River dist, Alaska, U.S.G.S., Special pub., pp 51-52, 1901.

3 - Capps, S.R., Bull. 630, U.S.G.S., The Chisana-White River Dist, Alaska, Plate IV, p.18, Fig.4, p.38.

have been developed later as an early stage in the pre-glacial stream erosion of the region.

Pre-Glacial Surface. - The main drainage channels such as the Chitina River, are along prominent structural lines, as pointed out by Moffit and Capps,[1] and are believed by them to have been established at a fairly early date. The earliest dissection of the Wrangell Range was probably by stream erosion, and a rugged topography is believed to have been in existence before the intense glaciation of the Pleistocene. The remnants of flat surfaces mentioned in the preceding paragraph may be correlated with evidence from neighboring parts of the range,[2] and their altitude and distribution make it very probable that they were developed in the early stages of the erosion of the region. For the most part they are too low to agree with the pre-volcanic surface. Rejuvenation of the streams, due to a broad uplift of the region, may be considered the cause of the dissection of these surfaces, which are now preserved only on the lower ridges that flank the main range. That mountain-making movements continued until very recent times in the Wrangell Range is shown by the disturbance of

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1 - Bull. 448, pp. 74 - 75.

2 - Capps, S.R., Bull. 630, Plate XVII, opp. p.76.

the lava beds and even of early glacial deposits in the Chisana - White River District, described by Capps. Consequently uplift in the Kennecott region at a fairly late time is not out of accord with the evidence elsewhere.

It is difficult to estimate the degree to which the country was dissected by stream erosion before the advance of the glaciers. The Chitina Valley was probably similar in its broad features to the present topography, and Moffit and Capps believe that the tributary stream drainage was well developed. We could find no evidence opposed to this view. It seems very probable that in the long period in the late Tertiary, during which the volcanics and their elevated platform were exposed to erosion, a topography at least approaching maturity had been developed.

Glaciation and the Present Surface. - The present land forms have been profoundly modified by the intense glaciation of the period which is probably now drawing to a close. In the high altitudes glaciation has undoubtedly been long continued, but as outlined above, stream erosion is considered the chief agent which had shaped the earlier drainage lines. Upon these channels the great glaciers of the Pleistocene have impressed their characteristic features, eroding broad U-shaped valleys in place of the narrower cañons, truncating projecting spurs and straightening the valley walls, and over-riding and

smoothing the lower ridges. From the difference in elevation between the mouths of hanging tributary valleys and the main glacial channels, Moffit and Capps[1] estimate the amount of deepening by glacial scour to have been between 1,000 and 1,500 feet.

No evidence of more than one period of glaciation has been observed in the Kennecott district. S. R. Capps,[2] however, has recently described indurated and deformed glacial deposits near the source of the White River. They are associated with lava flows, and are overlain unconformably by recent glacial deposits. The evidence is interpreted, however, as the record of an early Pleistocene glacial advance, separated by a long time interval from the latest glaciation, but nevertheless part of the same large period. From this information it seems fairly probable that there has been similar early glaciation throughout the Wrangell mountains, but in most places, as near Kennecott, the intense erosion of the recent glaciers has obliterated all earlier records.

The glacial period in this region has not yet passed. The broad valley to the west of the mines is still occupied by the great Kennecott Glacier, (Figs. 28 and 29) which descends from the ice-fields of Mt. Blackburn (16,140 ft.) to an alti-

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1 - Bull. 448, p. 44.

2 - Two glacial stages in Alaska: Jour.Geol., Vol.23, pp. 748-756, 1915, and Bull.630,U.S.G.S., pp.63-67, 1916.

tude of only 1,400 ft. Bonanza Peak still supports five short mountain glaciers, and even now one side of the outcrop of the Bonanza ore-body is attacked by a small glacier, which enriched its moraine with chalcocite until mining operations interrupted it. Elsewhere along the ridge, especially on Porphyry Mt., the cirques are occupied by "rock glaciers", (Fig. 22) which may be regarded as the dying efforts of true glacial action.[1]

An attempt is made by Moffit and Capps to outline, on their geologic map, the land areas which projected above the glaciers at the time of their maximum development. The line follows the topographic break between the smoothed and rounded contours of the lower slopes and the rough and angular forms of the summit regions. In general it may be drawn with reasonable certainty, but near the mines above Kennecott, the sharp arrêtes and difficult peaks are clearly due to the intersecting cirques of the present glaciers. An earlier topography, smoothed by over-riding masses of ice, could easily have been destroyed by these later changes; consequently the character of the present summit topography cannot be regarded as conclusive evidence that the entire ridge had not been over-ridden by the ice.

There is a slight amount of post-glacial erosion along the

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1 - Capps, S.R., Rock glaciers in Alaska: Jour.Geol.,Vol.18, pp. 359-375; Also Bull.448,pp.52-59.

PLATE VII

Kennecott, Alaska.

Fig. 19. The greenstone - limestone contact along the cliffs north of the Bonanza Mine.

Fig. 20. Fault breaking the greenstone-limestone contact southeast of the Bonanza Mine.

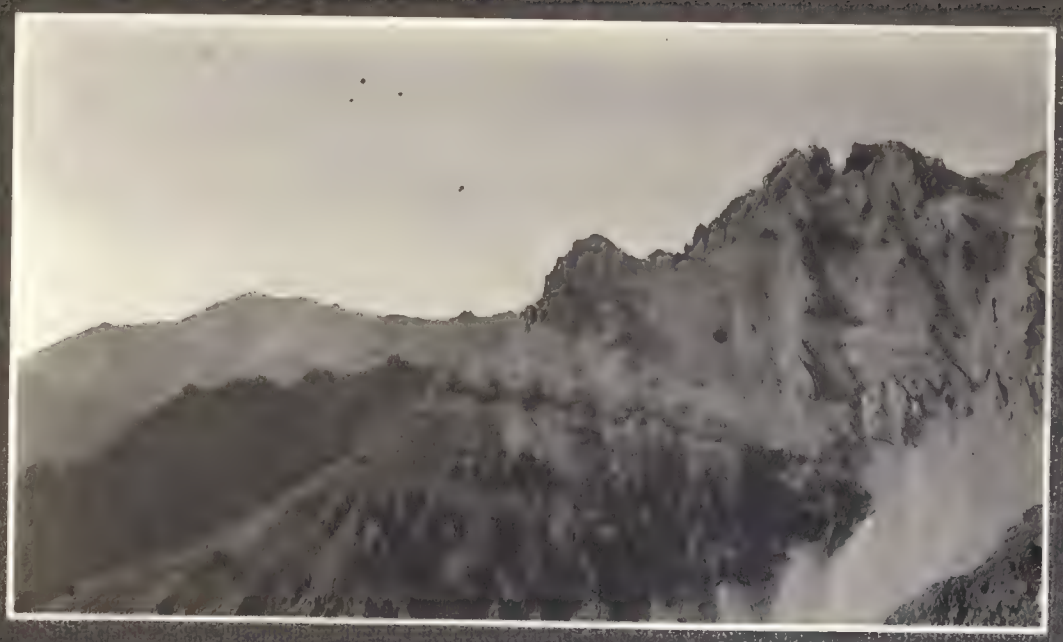

PLATE VIII

Kennecott, Alaska.

Fig. 21. The spur along which the veins of the Bonanza Mine out-crop. Note mine workings on the cliff faces.

Fig. 22. View to the south from the summit of Bonanza Peak. Porphyry Mountain in the centre, the Nizina and Chitina Vallies in the back ground and the Chugach Mountains on the horizon; McCarthy Creek cañon to the left; a little of the moraine of the Kennecott glacier on the extreme right.

PLATE IX

Kennecott, Alaska.

Fig. 23. The Chitistone limestone in Independence Basin, southeast of Bonanza Mine. The spur on which the Bonanza Mine is situated is shown in the background on the extreme left.

Fig. 24. An inclusion of black shale of the Kennecott formation in porphyry on northern side of Porphry Mountain.

Fig. 25. Chert and shale beds of the Kennecott formation along National Creek above Kennecott.

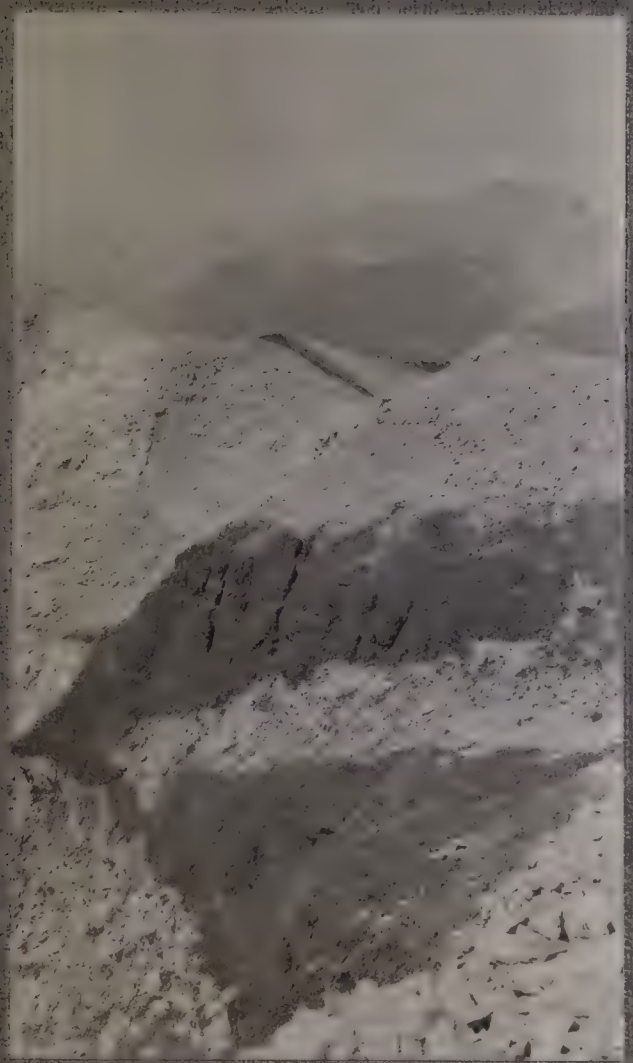

PLATE X

Kennecott, Alaska.

Fig. 26. An inclusion of shale of the Kennecott formation in porphyry on the north side of Porphyry Mountain.

Fig. 27. Inclusion of shale in porphyry, cut by a dike of a more basic type.

PLATE XI

Kennecott, Alaska.

Fig. 28. The Kennecott glacier and Mt. Blackburn from the summit of Porphyry Mountain. Note the greenstone-limestone contact on both sides of the glacier. The fold and reverse-fault above the contact are shown on the cliff between the main glacier and the tributary on the right.

Fig. 29. The Kennecott glacier seen from the summit of Bonanza Peak. Note the greenstone-limestone contact along the cliffs on both sides of the glacier, and the flat surface on the mountains on the west side. The peaks to the right are of volcanic material. The tributary glacier from Mt. Regal joins the Kennecott glacier in the foreground.

PLATE XII

Fig. 30. View of the Wrangell Range looking north from the summit of Bonanza Peak. Mt. Regal and the great ice-fall of the southern tributary of the Kennecott Glacier are on the right of center. Note the horizontal beds of volcanic rocks which form the higher peaks.

Fig. 31. View of the valley of McCarthy Creek from the summit of Bonanza Peak, looking to the northeast. Chitistone limestone beds form the cliffs in the foreground, with softer beds of McCarthy shale above, and the sediments (chiefly shales) of the Kennecott formation on the smoother distant slopes. The volcanic beds of the higher peaks are prominent. This view is panoramic with Fig. 30.

PLATE XIII

Kennecott, Alaska.

Fig. 32. The Jumbo Mine and Glacier, and the northwestern cliffs of Bonanza Peak.

Fig. 33. The Jumbo Mine and Glacier, beneath the southern cliff of Jumbo Castle.

Fig. 34. The limestone-greenstone contact along the cliffs north of the Jumbo Mine. The outcrop of the Jumbo Vein is marked by the small adit on the nearest spur on the right side of the picture, just above the contact. The Tram House of the Jumbo Mine is shown in the lower right foreground. The Kennecott Glacier may be seen to the left. The view is panoramic with Fig. 33.

PLATE XIII A

Kennecott, Alaska.

Fig. 34a. Bergschrund of the Jumbo Glacier. Northwest side of Bonanza Peak.

Fig. 34b. The contact of the Chitistone limestone and Nikolai greenstone (beneath) at a prospect near the Erie Mine. The thin shale bed at the bottom of the limestone is well shown.

Fig. 34c. The bench along the limestone-greenstone contact near the Erie Mine, about 1000 ft. above the Kennecott Glacier.

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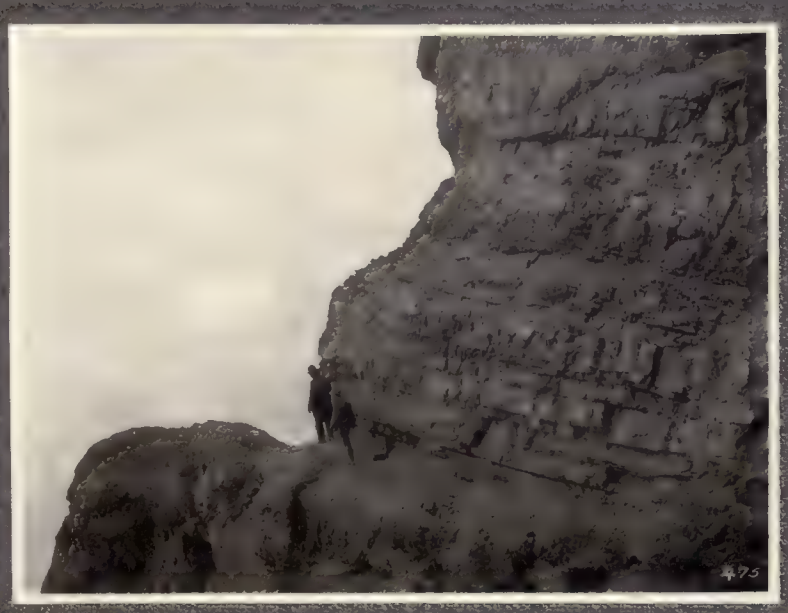
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lower courses of the streams from Bonanza Ridge, but as the glacial period is still in existence near the mines, water is an unimportant agent.

MINERALIZATION IN THE GREENSTONE.

The mineralization in the greenstone is a formation wide feature. Traces of copper are common in nearly all parts of the region where the rocks are exposed, but few prospects give much promise of eventually supporting mines.

Form of Deposits. The mineral deposits in the greenstone occur in the following forms (1) veins breaking across the bedding of the flows, (2) disseminated deposits of replacement origin, and (3) amygdule fillings. The first group is the most important from a commercial standpoint. The veins in the Kennecott district are rather short, and few were observed of sufficient persistence to carry them through the thickness of more than two or three of the flows. For the most part they are small, and are to be measured in inches or fractions of an inch, but in a few exceptions they attain a thickness of several feet, with their other dimensions correspondingly greater.

The disseminated mineralization is either related to definite veins, or to shear zones along which circulation of solutions could take place. No ores of this sort are known to be of value although large areas of the greenstone contain small

amounts of copper.

The distribution of the amygdaloidal deposits is of course limited to horizons of once vesicular lava, and like the disseminated mineralization, there is a dependence on neighboring veins or sheared zones. Near Kennecott, deposits of this sort are not common, although native copper and bornite were observed in amygdules in a few cases.

Gangue Minerals. Calcite and quartz are the commonest gangue minerals in the veins, although in some cases epidote becomes of equal importance. The veins are of replacement origin for the most part, as is clearly shown by the relations of their minerals to the wall work, but in several localities large quartz crystals lining cavities were observed, and there could be little doubt that open spaces had existed, and probably played an important rôle. Small veinlets of albite, usually associated with epidote, are found fairly commonly, and in a few cases, datolite was observed associated with the other gangue minerals.

The amygdule fillings are very probably of the same origin as the vein fillings. Pennine, delessite, (and possibly other chlorites), serpentine, and calcite are the usual minerals. Fine green borders of fibrous serpentine were apparently the first to form; a broader layer of pleocroic chlorite (pennine probably) commonly succeeds the serpentine, passing toward the center, and the interior of the cavities in many cases is formed of broader flakes of delessite.

Calcite is the last to form, and where it occurs, it is nearly always in the center. Quartz and epidote are less common in the amygdules. A mineral resembling prehnite in most of its properties, but not positively identified, occurs with native copper in a few cases, but the amygdules composed of zeolites, and native copper, which are plentiful in the White River district in similar rocks[1], were not observed in the Kennecott region.

Rock Alteration. The rock alteration accompanying the mineralization is similar to the general propylitization of the greenstone, but more intensive. Chlorite is more abundantly developed near the veins, and little of the original character of the work generally remains. Heulandite and a few other zeolites less positively identified (probably harmotone and epistilbite in two cases) replace the feldspar near certain veins. Calcite is wide-spread as the final product, replacing nearly all pre-existing minerals.

The order of mineral succession can not be stated in detail, but for the veins and the replacements of the wall rock, albite, epidote, quartz and datolite may be regarded as representatives of the earlier phases of the mineralization. Similarly the zeolites and calcite belong to the closing phases.

Primary Ore-Minerals. Bornite and chalcocite~~pyrite~~ are the most important of the ore-minerals. In some cases, pyrite

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1. Knopf, A., Loc. cit.

is common, but not in the vicinity of Kennecott. The bornite and chalcopyrite are clearly primary. Their contacts show the usual mutual outlines which are believed to be characteristic of primary relationships. The opinion has been expressed[1] that in certain cases the bornite is secondary, and should be expected to decrease with respect to the chalcopyrite with depth. As none of the deposits are more than prospects there is little positive evidence of changes in a vertical direction, but the microscopic relations, which are similar to those observed in ores of known primary character, show that this view is unwarranted. The ore-minerals corrode the rock minerals or the gangue, and are clearly of later formation. Calcite, however, is an exception, being in part later than the sulphides, as it distinctly breaks their grains in veins in many cases. The time relation between the ore-minerals and the zeolites is not known. Both bornite and chalcopyrite were observed in amygdules, usually with calcite, with which the sulphides were apparently contemporaneous.

Secondary Alteration. The amount of surficial alteration is small. The sulphides are themselves exposed to the air on the out-crops, and in no case is there a zone of complete oxidation. Malachite and limonite in varying amounts are always present, however. Native copper and cuprite occur in many of the veins and as disseminated specks throughout the rock or in the amygdules. It is impossible to decide

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1. Moffit, F. H. and Capps, S. R., Bull. 448, p. 95.

from the evidence available, whether the native copper was derived from pre-existing sulphides or was deposited as an initial constituent of the ores. The cuprite may be seen under the microscope to be a product of the oxidation of the native copper.

Deposits near the Bonanza Mine. Chalcocite and covellite are not abundant, but occur in small amounts in all the bornite ores studied. In nearly all cases, the chalcocite is clearly a replacement of the bornite, but occasionally the minerals are associated in structures which are difficult to interpret. In a specimen from a vein west of the Bonanza Mine, the chalcocite contains smooth blebs of bornite with shapes similar to blebs of the graphic structure. Veins of chalcocite in the bornite, however, offer conclusive proof that at least part of the chalcocite is of replacement origin. The chalcocite is slightly altered to malachite, which forms series of straight parallel veins in it, revealing the coarse grain, and crystal structure of the sulphides. Etching with nitric acid or potassium cyanide developes fine persistent cracks, oriented in only one direction in each grain, and parallel to the direction of the malachite veinlets. The structure is that commonly exhibited by orthorhombic chalcocite. The large grains of chalcocite frequently include smaller grains of the bornite, with no apparent interruption of the crystal structure of the chalcocite. The bornite etches with its usual fine grained pattern, and shows no relation to the orientation of the surrounding chalcocite.

None of the prospects in the greenstone near Kennecott

expose more than the upper ten feet or so of the deposits, consequently no positive information is available concerning the depth of oxidation and secondary sulphides.

Kuskulana District. In the Kuskulana District, a deposit on Nugget Creek is exposed to a depth of about 300 ft. and as its ores are very similar to the material in the greenstone near Kennecott, they offer valuable evidence concerning the nature of enrichment in the greenstone.

The ore-bodies at Nugget Creek consist of lenses of bornite, with subordinate amounts of chalcopyrite and chalcocite, along a shear-zone in the Nikolai greenstone. The bornite and chalcopyrite are associated in structures, commonly regarded as typical of primary ores. The chalcocite, which is apparently as abundant on the lowest level as near the surface, is of two ages. For the most part it is associated with the bornite in a structure identical with that commonly exhibited by the bornite and chalcopyrite in primary deposits, which in places merges with typical graphic structures of bornite and chalcocite. (Figs.101,102). There is distinct evidence of attack on the bornite grains by the chalcocite, however, and there can be little doubt that part of the chalcocite is of replacement origin. In addition to the chalcocite in these relations to the bornite, there are fine veinlets of chalcocite which are clearly imposed upon the earlier structures. They break the bornite blebs, but disappear when a chalcocite area is encountered. In some cases, the crack followed by the veinlet can be traced across the

chalcocite areas; in others, it is apparently of submicroscopic size. (Similar relations were observed at the Superior Prospect, near Engels, California; (see page 138).

The fine veinlets of chalcocite are most probably related to a recent surface of rapid mechanical degradation. As the ground remains frozen throughout the year except at shallow depths, even this small amount of enrichment can hardly have taken place in post-glacial time. It is possible, however, that it may have occurred in an interglacial period, during which higher temperatures prevailed than those at present.

The origin to be assigned to the earlier chalcocite depends upon the interpretation of the graphic structure and the other closely associated form. The latter presents most of the properties of the graphic structure and is surely of similar origin. If the chalcocite in these structures is a contemporaneous intergrowth with the bornite, slightly modified by subsequent replacement, the chalcocite is of primary origin; if the chalcocite in the graphic structure is entirely a replacement of bornite it is not necessarily primary, and the evidence from other districts suggests that it may be the product of deep enrichment. The pre-volcanic surface, which probably covered this region, or the later surface, developed during the pre-glacial stream erosion, may have afforded the necessary conditions for deep enrichment.

Kotsina District. Still further to the west, on Elliott Creek in the Kotsina District, similar bornite ore occurs in the greenstones, and a study of polished specimens from the Mineral King claim shows a very interesting type of alteration of the bornite to covellite, chalcocite and chalcopyrite. The bornite possesses a medium grained structure which is emphasized by the tendency for the development of covellite and chalcocite to be limited to certain grains. The alteration proceeds by means of a net-work of fine, irregular veinlets, almost sub-microscopic in some cases, which are about equally developed in any part of a single grain. It seems as if certain areas of bornite were literally "rotting" to covellite and chalcocite. The covellite is the earliest, and is partially altered to chalcocite. On the other hand, bands or areas between the grains appear more resistant. The bornite has its true color, and where it is penetrated by chalcocite or covellite, well-defined veinlets are found, and not the fine lacy patterns described above. The resistant type of bornite, however, contains numerous fine spines of chalcopyrite, distributed in a lattice pattern. The chalcopyrite rarely occurs in the grains which are altering to covellite and chalcocite. The chalcopyrite is earlier than the copper sulphides, for their veinlets break the spines in some cases, but it is closely associated with their development.

Similar microscopic relations with the exception of the confinement of the replacing sulphides to grains or zones in the

bornite, have been commonly observed in ores of known secondary origin. Only the superficial parts of the deposits are known, but there is no reason to doubt that these changes were caused by descending solutions, although probably from a preglacial surface rather than the present one, for there can be little enrichment in frozen ground.

Summary of Important Features. The most striking and significant fact related to the mineralization in the greenstone is the wide distribution of the deposits, and their great similarity over the entire region. The rock alteration, the gangue minerals and the primary sulphides show little variation throughout the district. A few small deposits on the west side of the Kuskulana glacier seem somewhat different, as pyrite and magnetite become abundant, and garnet is prominent in the gangue, but in these cases there is evidence that the ores are related to an intrusion of porphyry, and probably are of very different origin than the usual type of mineral deposit in the greenstone.

The association of calcite, quartz and epidote as the chief gangue minerals, with chlorite, datolite and small amounts of zeolites, and bornite and chalcopyrite as the common ore-minerals is common throughout the region, and offers an interesting comparison to other members of the world-wide class of copper deposits in basic lavas.

The small size of the deposits and their irregular bunchy character are points of more than scientific interest, as it makes the outlook for the development of notable ore-bodies under the present conditions far from promising. However, the contrast with the exceedingly rich ores of the overlying limestone may cause one to underestimate their value.

ORE DEPOSITS IN THE CHITISTONE LIMESTONE.

The ore-bodies of the producing mines of the Kennecott District are all in the Chitistone limestone. The mineralization is especially remarkable for the great size of the sulphide bodies, the purity of chalcocite of which they are formed, and the almost complete absence of silica in the veins or in the wall rock. The deposits are monotonous from the standpoint of the mineralogist, for other sulphides than chalcocite are rare, but in the few places in which a variety of minerals were found the complexity of their relations to each other revealed by microscopical study of polished surfaces, has offered numerous problems of absorbing interest. The greatest single problem in connection with the Kennecott ores is the secondary or primary origin of the chalcocite. Consequently, in this portion of the paper, which deals with description rather than deduction and speculation, the ores will be discussed without the usual separation into those of primary origin and those of secondary origin.

Geologic Situation of Mines. The ore-bodies worked by the Bonanza and Jumbo Mines are situated in the lower beds of the Chitistone limestone, at the bottom of the dolomitic horizon and to a certain extent in the upper beds of the gray limestone, described on page 217 . The ores at the Erie Mine are in the lowest beds of the formation, immediately above the greenstone contact, but at the Mother Lode Mine on the eastern side of the ridge, the ores now exposed are about 1000 ft. stratigraphically above the contact.

Structural Relations. The forms of the ore-bodies in the two great mines are very similar, and a general description may be given which applies to both. The chalcocite, which is the abundant ore-mineral, occurs in a definite fissure zone with a vertical or a high dip. In places it widens to great massive bunches, but in general the tabular form is maintained. The bottom of the ore with some local exceptions is against the "flat fault", described on page 225. The fault, as has been stated, is parallel to the bedding or is slightly steeper. In the Jumbo Mine, it is a prominent feature; in the Bonanza Mine, there is evidence of its existence, but it does not form as definite a lower limit for the ore. The intersection of the main vertical fissure zone and the flat fault is a particularly favorable locus for the mineralization. The largest ore-bodies in both mines are formed by the widening of the vertical veins along this horizon. (Fig. 35)

The vertical fractures as well as the ore are strongest near the flat fault, and tend to die out, as one passes higher stratigraphically. There is no evidence of notable movement along them. In a few places, where the mining operations have penetrated the ground beneath the fault flat, the vertical fissuring apparently dies out or decreases very greatly. There is a strong suggestion from the relationship that the vertical fractures and the flat fault were of contemporaneous origin. As has been mentioned, there is evidence

suggesting rather violent thrust movements along the plane of the flat fault. Vertical breaks, relieving differential stresses, would be very probable accompaniments of such movement, and the vertical fractures, which have afforded the chief channel ways for the ore-forming solutions may have been formed in this way, but the failure of the vertical fractures to continue below the flat fault may possibly be due merely to displacement along it.

Cross-breaks are numerous. Several series were observed and studied. For the most part, they are pre-ore, but in the few cases, where there is post-ore movement it amounts only to a few feet. The ore tends to make out along the earlier cross-breaks to a slight degree, but rarely extends far from the main fracture zone although frequently far enough to cause a local swelling of the vein. In parts of both mines, more than one vertical fissure is mineralized, and in these localities, good ore-bodies are common along cross-breaks between the two veins. Bedding planes have played a similar role in directing the ore-solutions but are less prominent than the cross fractures. Zones of fine chalcocite veinlets are common in certain portions of the ore, but disseminated sulphide bodies do not occur. In general, the ore shows a marked dependence upon the main vertical or nearly vertical fracture system, and is only slightly modified by the other structural features with the exception of the flat fault, which usually forms the bottom of the ore. The relations are

generalized in the idealized sections shown below.

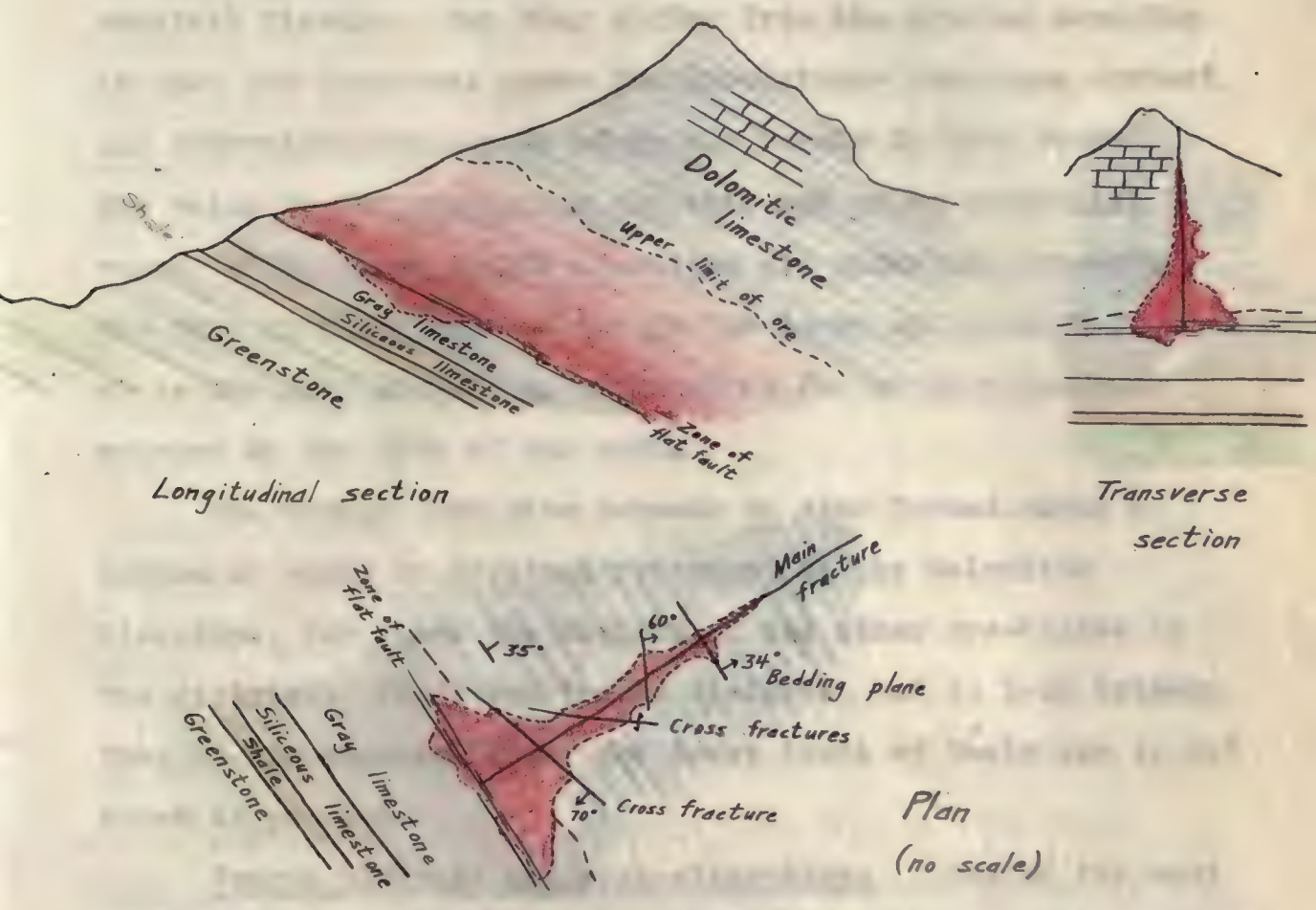
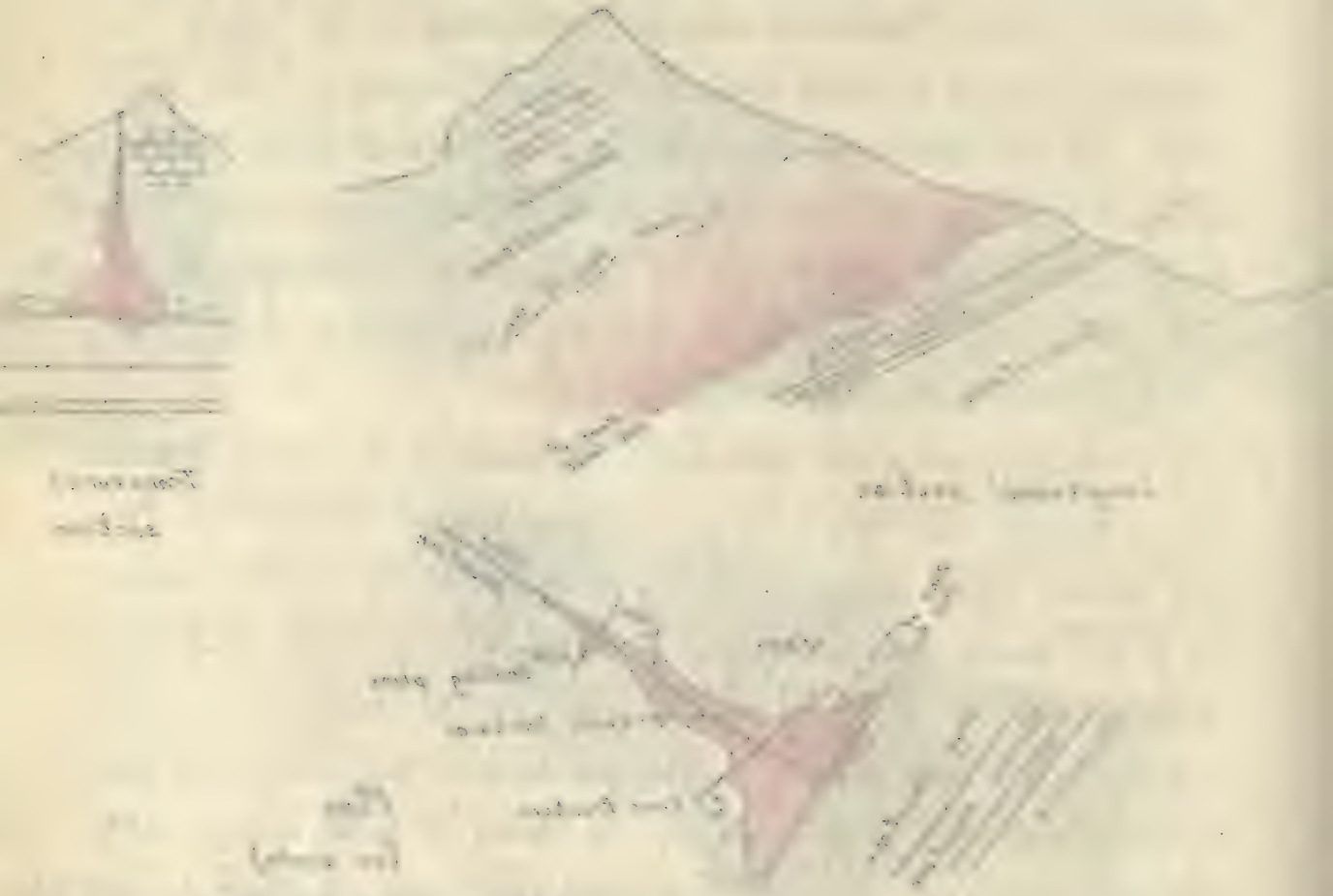


Fig. 35. Idealized longitudinal and transverse sections of the ore-bodies of the Kennecott Mines.

The largest ore-bodies are in the lower portions of the vertical fracture zone near the flat fault. Passing upward, stratigraphically, the mineralization becomes weaker, and the line representing the upper limit of minable ore is, in a broad way, strikingly parallel with the dip of the flat fault and the bedding of the limestones. (Fig. 35)



At the Erie Mine, the ores are also formed along vertical fissures, but they differ from the greater deposits in that the fractures cross the greenstone- limestone contact, and mineralization occurs along the breaks in both rocks. The veins in the greenstone are thin and of no commercial value, while those in the limestone are wider and promising. The ores in the limestone are in the lower siliceous beds, or in the grey limestone, at least as far as they had been exposed at the time of our work.

The Mother Lode mine depends on ores formed along a system of steep or vertical fractures in the dolomitic limestone, far above the horizon of the other ore-bodies of the district. The fissuring is distinct, but is less intense than at the Bonanza Mine. The lower limit of their ore is not known at present.

Gangue minerals and rock-alteration. One of the most remarkable features of the ores in the Chitistone limestone is the great simplicity of the gangue minerals, and the lack of silicification of the wall rock. The wall rock is commonly recrystallized along the veins, forming coarse grained masses of calcite and dolomite, but in many places, stringers of chalcocite occur directly in limestone of normal grain, which even under the microscope, shows no alteration of any sort. Only a few small grains of quartz were observed in a study of a large number of thin sections. No silicates were detected either in the field or in the course of the laboratory study of the material collected.

The recrystallization of the limestone along the veins, and the deposition of new calcite, or dolomite as vein-filling, is probably a phase of the mineralization, but evidently preceded the development of the sulphides in some places for in many cases the coarse crystals of the carbonates were observed to have been attacked along their cleavages or other lines of structural weakness by veinlets of chalcocite. The formation of the carbonates, however, extended considerably beyond the limits of the ore, and consequently the continuation of the fractures is marked by the veins of carbonates. Barren veins of these minerals are common in various parts of the Chitistone formation, however, as would be expected in a limestone country.

The gangue minerals in the veins at the Erie Mine show an interesting dependence on the wall rock. In the greenstone, quartz predominates and calcite is subordinate. The same fracture, followed into the limestone contains a gangue composed only of calcite and dolomite with no quartz.

Ore-minerals. Relative abundance. The ore-minerals, with the exception of obvious products of oxidation, are as follows, listed in the order of their quantitative importance:- (1) chalcocite, (2) covellite, (3) bornite, (4) enargite, (5) chalcopyrite, (6) luzonite(?), (7) tennantite, (8) pyrite, (9) sphalerite, and (10) galena. Of these, chalcocite is by far the most important. In the field, we estimated that it formed 90 - 95% of the sulphide ore, and no modification of

this figure seems necessary from the results of laboratory work. Covellite is fairly abundant, compared with the remaining minerals, and when its wide-spread distribution in fine threads and laths throughout the chalcocite is taken into account, it is not unlikely that it forms from 3 to 5% of the ore-minerals. The remaining sulphides probably constitute less than 2% of the ore. Of these, bornite is the most generally distributed. Grains over an inch in diameter are very rare, however, but small specks the size of a millemeter or less in diameter are common. Locally, enargite is important. In the Bonanza Mine it is probably more abundant than the bornite, but for the district as a whole, bornite undoubtedly forces it into fourth place. Chalcopyrite occurs megascopically only in a few small bunches, and is so rare, that it has been mistaken for gold by the miners. Luzonite (?) and tennantite are not uncommon under the microscope, but were not observed in the field. Pyrite is noticably absent in most parts of the deposits, and its total amount is exceedingly small. Sphalerite and galena are microscopic rarities.

Chalcocite. Two distinct types of chalcocite occur in the deposits in the Chitistone limestone, which we termed for convenience in the field, Steely chalcocite and crystalline chalcocite, respectively. The former is a compact massive

mineral, with no apparent grain, a conchoidal fracture, and a metallic steely luster. The crystalline chalcocite appears to have a granular structure on a fracture-surface, as if the material were composed of an aggregate of individual crystals of about the coarseness of a medium-grained marble. No crystal faces were observed on any of the grains, however, but the crystalline appearance is largely due to an imperfect cleavage.

The "steely chalcocite" is most abundant in the Bonanza Mine, the "crystalline" in the Jumbo Mine. The two types commonly grade into each other without sharp boundaries, but in a few rare instances, bands of the coarse material were found in the fine and visa versa.

The distinction between the two types is lost completely on the freshly polished surface, for both assume the same even bluish tint in reflected light. In the course of a few hours, however, a slight tarnish usually forms, revealing the grain of the material, and often the crystallographic structure. In the coarser grains, a pattern of triangles or rectangles is formed by lighter bands or strips cutting areas which tarnish to a deeper blue. (Fig. 119) The structure is identical with the lattice structure, previously described (page 174, figures 146,152).

Etching the polished surfaces with dilute nitric acid and with dilute potassium cyanide solution usually reveals the grain of the mineral. The crystalline chalcocite appears com-

posed of large grains cemented by smaller. (Fig. 107). Both large and small grains develope lattice patterns when etched, the smaller ones imperfectly as would be expected. Occasionally the smaller grains develope only one set of strong lines, similar to the orthorhombic etch-cleavage of chalcocite, but the structure is very subordinate. The steely chalcocite, when etched with nitric acid, yields irregular patterns of short curved or straight cracks with no definite orientation which produces a surface strikingly similar to that of crackled porcelain. (Fig. 105) Potassium cyanide solution on the same material brings out the fine grain of the mineral, and here and there develops an imperfect lattice pattern within the grain boundaries.

In other cases, however, both in steely and crystalline chalcocite, the original grain of the material seems lost. The polished surface is finely mottled with tiny dots of light blue and white, closely packed, with here and there a larger bluish area. Etching with the reagents merely develops a rough solution surface with no apparent structure in the mottled material. The bluish areas seem more resistant to cyanide, and usually yield a lattice pattern. Much of the crystalline chalcocite of the large ore-body of the Jumbo Mine is of this sort.

Another structure of interest in the chalcocite, although far less abundant than those previously described, is a peculiar concentric form assumed by the mineral, in small, localized spots in the ore. Where developed on rather a fine

scale, the chalcocite appears as if made up of an aggregate of small pea-like grains; the field name, pebbly chalcocite, is descriptive and will be used in referring to it. On the polished surface, the structure of the mineral is emphasized by concentric cracks in the individual grains, or by scalloped veinlets of carbonates. Small open spaces rarely exceeding 6 in. in their greatest dimensions have been observed in the ore, and in a few, the chalcocite of the walls possesses a well developed mammillary surface. The chalcocite, or the mineral which it replaces, may most reasonably be interpreted as an open space filling.

The various structures of the chalcocite are well brought out by veinlets of carbonates or other alteration products which are abundant in all parts of the ore-bodies. The lattice structure is particularly well shown in its various degrees of fineness (figures 103 and 116) As has been mentioned, the concentric structure is likewise revealed by the carbonate veinlets, and much more clearly than it can be shown by etching.

With the exception of a certain fraction of the covellite, which is plainly associated with the carbonates, the chalcocite is the latest sulphide to form. In the case of every other mineral in the list on page 309, there is clear evidence that it has suffered partial replacement by chalcocite, in some parts of the deposit at least. The relative ease of replacement of the earlier minerals by chalcocite varies notably as is commonly found to be the case in other camps. Bornite, as usual, goes

most readily with chalcopyrite a poor second. Enargite and tennantite are less easily replaced, but not as resistant as the luzonite(?) which often remains as fine veinlets or rings, partially corroded, in the chalcocite after all neighboring material had been consumed.

The relations between the chalcocite and other sulphides will be described in greater detail in the paragraphs dealing with the other minerals.

Careful chemical studies of chalcocite from the Bonanza and Jumbo Mines have been made in the Geophysical Laboratory in Washington. Two analyses and specific gravity determinations have been published[1], and are as follows:

Specific Gravity at 25°	Per cent Cu	Per cent S	Per cent Fe	Per cent SiO_2	Total
5.610	77.99	21.48	0.26	0.13	99.86
5.606	77.56	21.55	0.55	0.18	99.84

The analyses of chalcocite collected during our work in 1915 are in striking accord with the earlier results. Material from the Jumbo Mines yielded the following values:-[2]

Specimen	Steely glance	Crystalline glance
Cu	77.90	77.88
Ag	.07	.09
As	.06	.04
Fe	.17	.17
S	21.33	21.48
Insoluble Gangue	.10	.09
Ca O		.11
Mg O		.02
CO_2 (?)		.11

1. E. Posnjak, E.T.Allen, and H.E. Merwin, Loc.cit., p. 508.
2. E.T. Allen, private communication Dec., 1915.

Coarse grained crystalline glance from the Bonanza Mine was also found to have almost the same composition that the other chalcocites from the region have. Dr. Allen writes:"I find the copper to be 78.007., the silver 0.05%, the insoluble gangue 0.03%. It also seems to contain a trace of arsenic. It seems to me that the remarkable uniformity in composition of such a great body of ore is very significant as to the uniformity in the chemical conditions of formation."

The chalcocites sent to the Geophysical Laboratory were selected after mineralographic examination as examples of as pure material as could be obtained. Very minute grains of bornite were observed under the highest magnification, and their presence probably accounts for the iron in the analyses. In some specimens, especially the steely glance, fine grains of luzonite (?) occur, and possibly a little enargite. The arsenic is due to the presence of these minerals without doubt. A little covellite was seen as very fine threads in the chalcocite, but almost negligible in amount. The surfaces of the chalcocite exhibited the faint bluish mottling common in the Kennecott ore.

Concerning specific gravity determinations on the new material, Dr. Allen writes:[1] "I have determined the gravity of both Kn 1166 (crystalline chalcocite from the Bonanza Mines) and Kn 1200z (crystalline chalcocite from the Jumbo Mine) by both the Archimedes and the picknometer methods, and find, contrary to our expectations, a similar porosity in both. The

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1. Private communication, (Jan. 1916).

specimen Kn 1200z however is still nearly 2% lighter than a solution of Cu S in Cu$_2$ S should be. We can at present account for this only by supposing the specimen to possess that much pore space in capillaries too fine for water to penetrate under our conditions. The results are as follows:-

Kn 1166		
a.	Archimedes method at 25	5.591
b.	Piknometer " " "	5.628
Kn 1200z		
a.	Archimedes method at 25	5.478
b.	Piknometer " " "	5.531

Covellite. Covellite of two distinct ages may be recognized with certainty in the Kennecott ores. Part of the covellite is earlier than the chalcocite, and seems associated with the primary mineralization. An even greater amount, however, is conclusively shown, both by field and microscopical evidence, to be the first product of the oxidation of the chalcocite. As this part of the covellite is closely associated in its development and distribution with malachite, azurite and limonite, it will be considered on the pages dealing with oxidation. The earlier covellite occasionally occurs as broad crystalline bands through the ore, but it is commonest as aggregates of short laths scattered in the chalcocite. Locally, the blunt crystals may be abundant enough to resemble the distribution of feldspar laths in a diabase (Fig. 109) but ordinarily they are very small and form a subordinate part of the

total sulphide. Fine threads of covellite are almost always present, even in the purest chalcocite.

Bands, an inch or so wide, of coarsely crystalline covellite penetrate the massive chalcocite in a vein-like manner in several places but when studied under the microscope, the chalcocite is clearly shown to be later, as it forms fine veinlets along the boundaries of the covellite crystals and even breaks across them. (Fig.111) The covellite bands undoubtedly formed as veinlets in an earlier sulphide. In several cases, the chalcocite near the covellite contains residues of bornite, and it is most probable that in many cases at least, the covellite was developed in that mineral. The covellite crystals have their longer axes perpendicular to the course of the vein, and on the polished surface, they offer a striking exhibition of the pleocroic properties of the mineral, varying from a deep blue parallel to the plane of polarization to pale bluish white when at right angles.

In a few specimens, believed, when collected, to be entirely composed of covellite the microscope revealed a complex aggregate of blunt covellite laths, with chalcopyrite and bornite filling the small angular spaces between them (Fig.110) a relation very similar to the feldspar laths and the ferromagnesian minerals in a medium grained diabase. The covellite laths are sharply bounded, and break across bornite- chalcopyrite contacts without the slightest change. The ordinary criteria of sequence among minerals of igneous rocks, if applied here

would put the covellite earlier than the bornite and chalcopyrite for the latter apparently moulded themselves about the covellite crystals. On the other hand the usual sequence elsewhere in the deposit argues that the covellite is later than the iron sulphides. The disregard of the covellite for bornite or chalcopyrite grains is however difficult to explain on this basis, for under ordinary conditions of replacement, the greater ease of the alteration of bornite to covellite than of chalcopyrite to covellite is very definitely shown. It is possible however that the chalcopyrite in these associations is a replacement of bornite, and developed with the covellite, but the blocky grains in which it occurs are unlike the forms commonly assumed by chalcopyrite of such origin.

Bornite. In nearly all parts of the deposit, small amounts of bornite are found, but it is less abundant in the crystalline type of chalcocite, and most abundant in steely glance in the Erie Mine and certain parts of the Bonanza Mine. It is most common in small grains and patches with rather smooth outlines in chalcocite. They rarely exceed an inch diameter, and are most abundant as tiny specks of microscopic size. The larger grains are often broken by veinlets of chalcocite which afford clear evidence of replacement. (Fig.118) The veinlets usually follow cracks in the bornite, which may contain malachite or limonite in some cases. The oxidized material, however, rarely extends beyond the limits of the bornite, and only in the case of the larger veins does the crack continue on into the chalcocite

field. (Fig. 117). The malachite veinlets in regular lattice patterns in the chalcocite either do not extend into the bornite or else follow curving cracks in it without yielding definite patterns. (Fig.120). The bornite etches with its usual fine-grained lines but their orientation rarely agrees with the structural directions of the surrounding chalcocite.

Definite lattice patterns between bornite and chalcocite, similar to those observed in Bisbee ores (page 174) do not occur at Kennecott, but in some places, the distribution of faint bluish residues and the pattern of blue and white chalcocite strongly suggest the last stages of replacements of the lattice type. This impression gains support from the occurrence of residual spines or more correctly plates of bornite in chalcocite, in symmetrical orientation to the pattern in the chalcocite, which is strikingly similar to the association common in bornite-chalcocite ores from Butte and Bisbee, where the lattice structure is important. In places where the intersecting spines are abundant, the relations resemble forms assumed by certain intergrowths of minerals (magnetite and ilmenite for example) and of artificial products (chalcopyrite and bornite; certain iron carbon compounds in steel.) Careful study, however, of the contacts invariably yields evidence of chalcocite replacement of bornite, and establishes the residual nature of the spines.

The lattice structure is shown also by spines of chalcopyrite in bornite, similar to the relations described previously at Engels, LaFleur Mt., Copper Mt., and Seven Devils. The chalcopyrite in many cases shows the same dependence on chalcocite veinlets in the bornite as has been noted in the other deposits, but the intense development of chalcocite in the Kennecott ores usually masks the evidence of incipient alteration. However, it is clear here, as in the other camps that the chalcopyrite is a product of the reactions by which the chalcocite was produced from bornite. In places the change becomes of quantitative importance, and the intersecting spines in the fine grill become so numerous as to yield an almost solid mass of chalcopyrite. (figures 154)

Certain narrow strips of bornite often with sharp offsets seem less subject to alteration to chalcopyrite, and usually remain untouched. They greatly resemble veinlets of bornite in chalcopyrite, and in the extreme cases of chalcopyrite formation it is difficult to escape from the interpretation that chalcopyrite was the earlier mineral. However, by tracing the relations from the incipient stages, where a faint band of chalcopyrite spines is forming along the margins of these strips of resistant bornite to the final stages, where the main field of bornite has been completely altered and only the strips remain, the sequence of bornite to chalcopyrite may be firmly established.

By these changes, intimate mixtures of bornite and chalcopyrite are produced. From them, the bornite is extracted

in many cases by alteration to covellite or less commonly to chalcocite. Extremely complex patterns of covellite, in fine lines, specks or veinlets in chalcopyrite result, so intricately and finely spaced that under low magnifications, the surface appears almost as if it were a single mineral with a pecular shade of yellow.

No typical graphic structures between bornite and chalcocite were observed in the Kennecott ores, but in some cases, in chalcocite clearly of replacement origin, residues of bornite assume forms very similar to the shapes of the blebs in graphic areas. These sub-graphic structures, as they may be termed, are usually on the edge of bornite areas, and are part of broad borders or margins of chalcocite which are without question a replacement of the bornite.

In the preceding paragraphs, the results of various alterations of the bornite have been considered. The relations of the bornite to contemporaneous or earlier sulphides remain to be considered, and will be treated under the headings of the following minerals.

Bornite continued to form under the conditions which produced the earliest covellite, if the evidences presented on pages 256-257 is to be accepted. This weak continuation or renewal of bornite formation is shown by fine veinlets, which break later structures, and later minerals as luzonite or, rarely, the covellite.

A puzzling occurrence of bornite in nodules about the size and shape of pigeon's eggs was noted near the Erie Mine. The nodules are in the lower siliceous limestone, and apparently have no connection with the veins or ore-bodies either in the limestone or in the underlying greenstone. No structure could be observed in the bornite which would suggest a replacement of a fossil or of some impurity in the rock.

In one nodule studied microscopically the bornite is cut by numerous veinlets. The centers of the veinlets are usually malachite and calcite with limonite on the sides. They are bordered by thin margins of covellite which in turn is succeeded inward by narrow bands of chalcocite. Many grains of the bornite contain fine lattices of chalcopyrite spines which in places range down to almost submicroscopic size. Certain bornite grains, with unusual yellowish tints, are most probably filled with chalcopyrite of this character, too fine to be detected by our highest magnifications.

The nodule presents a wondefully complete record of the alteration of bornite. The slight stains on the surrounding limestone indicate that little except water and oxygen and calcium carbonate have been added to the nodule and that little has been removed. Consequently, the chief work of the oxidizing process has been to rework the mineral combinations, with little addition or subtraction of material. As the alteration advances into the nodule along cracks and seams, the copper of the bornite is transposed into chalcocite. The iron liberated by

this reaction is in part forced ahead of the main alteration and concentrated in the protected interior producing the lattice of chalcopyrite, and in part finds its way into the principal channels, where, with the acidity of the solutions reduced by calcium carbonate from the limestone, it is oxidized and hydrolyzed to limonite, and therefore little iron escapes beyond the limits of the nodule. The continuing attack of oxidation yields covellite from the chalcocite with malachite as the final product.

The nodule affords convincing evidence of the details of the alteration of bornite to secondary sulphides. It is not a case of enrichment if the entire module is considered for no copper has been added, but its processes are identical with those which take place in the enrichment of larger ore-bodies. The sequence of alteration products is not simple but it may be illustrated fairly completely by the diagram below. The alteration of one mineral to the other is in the direction of the arrows.

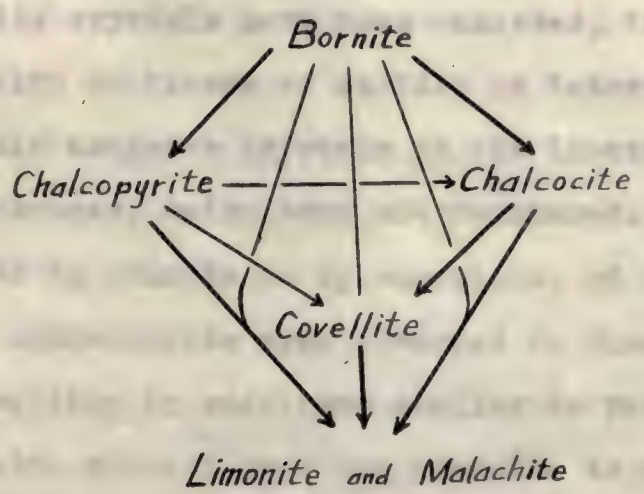

Fig.36.Diagram of mineral sequence in bornite nodule from limestone near Erie Mine.

Enargite. Enargite occurs abundantly in coarse crystalline masses in a few places in the Bonanza Mine, and in small amounts throughout the ore, especially in the steely chalcocite. None was observed megascopically in the Jumbo ore. In the crystalline chalcocite, which is the most important type in this ore-body, there is little even under the microscope. On the whole, it is far less abundant than bornite, although a considerable mass of it was exposed on the 100'L of the Bonanza Mine, where the mineral was first observed by Dr. Bateman.

The enargite is usually associated with chalcocite, which replaces it, yielding a peculiar brecciated structure, with angular fragments of the enargite set in a cement of blue chalcocite. In some cases etching develops a well-defined triangular pattern in the chalcocite. The enargite apparently alters less easily than bornite, and the replacement to chalcocite generally does not seem to be far advanced.

The relations of the enargite to the other sulphides (except the chalcocite) are not definitely shown. In most cases, it is clearly a replacement of the carbonate of the wall-rock. Small definite crystals have been observed, in the unaltered limestone, with no traces of earlier or later sulphides. (Fig. 121)

Certain enargite crystals in the limestone show signs of mechanical changes, being bent and fractured. The fractures were cemented by calcite or by covellite, of the early type. Bornite and chalcopyrite were observed in close associations with the covellite in relations similar to those described on page 256 which suggest that the enargite is an earlier product than the iron-bearing sulphides.

Under the microscope, the polished surfaces of certain sections of the enargite crystals were found to be distinctly pleocroic, when the specimen was retated in polarized light. When the longer axis is parallel to the plane of polarization (the plane of the reflecting mirror), the mineral assumes a pinkish tint; at right angles it becomes white or slightly bluish when contrasted with the normal enargite white. Many sections however show no trace of pleocroism.

Chalcopyrite. Besides the chalcopyrite previously described which is a replacement of bornite in the lattice structures, the mineral also occurs in small grains which are clearly contemporaneous or earlier than the bornite with which they are associated. In the typical cases, the two ages of chalcopyrite may be readily separated, but in less definite forms, in which more complete replacement may have obscured the original relations, it is difficult or impossible to distinguish them.

The earlier chalcopyrite forms clean grains, associated with the bornite in mutual structures for the most part, but occasionally corroded by the bornite or broken by its veinlets in ways which convincingly show its earlier origin.(figure 126)

The chalcopyrite, however, is an uncommon feature in the deposits, and probably never was of importance.

Luzonite. Veinlets or grains of a pinkish mineral, which has not been positively identified, have been observed in a number of specimens in the chalcocite or the less common minerals. It agrees in mineralographic properties with the

luzonite in Dr. Murdoch's standard collection. It resembles enargite in general properties, but possesses a deeper pink color in reflected light and is never pleocroic.

The mineral does not exist in sufficient quantities in the Kennecott ores to permit analytical determination, but qualitative tests on small fragments indicate the presence of arsenic and the absence of antimony and bismuth.

The luzonite, or at least the "pink enargite", is a rather late product, for its veins break all other sulphides except chalcocite. It replaces bornite in the complex chalcopyrite-bornite mixtures, producing an apparent lattice of chalcopyrite in a field of luzonite. Elsewhere it breaks the chalcopyrite in veinlets, and even cuts boldly across the broad plates of covellite. In several cases, it forms borders around the crystals of covellite, as if deposited at a later time.

It plays a prominent part in the peculiar concentric structures found in various parts of the ore, and preserves the curves of these textures even after the less resistant minerals have been completely replaced by chalcocite.

Tennantite. Tennantite is rarely abundant enough to be visible in the hand-specimen, but it is common in certain complex mixtures of bornite, chalcopyrite and covellite. It is in part a replacement of chalcopyrite, as corroded cores of this mineral are common in the tennantite grains. The grains, however, usually possess crystalline outlines, and their arrangements in many cases, suggest that they were formed along the walls of open

spaces.

The crystals are often rimmed with thin borders of chalcopyrite which indicates conclusively a recurrence of the formation of this mineral. Fine veinlets of the later bornite also cut the tennantite crystals. The tennantite is also partially replaced by luzonite which develops in one or two instances a lattice structure identical in appearance with that between bornite and later minerals. The tennantite is relatively resistant to replacement by covellite and chalcocite.

Pyrite. Pyrite is very uncommon in the ore-bodies, but it is fairly wide-spread as a sparse scattering of small cubes in the lower siliceous beds of the Chitistone formation, where it apparently has no connection with the mineralization which produced the copper deposits. Under the flat fault in the Jumbo Mine, a few small bunches were found associated with partially oxidized copper ores and much limonite. It is possible that these may be of the sort previously mentioned, and were in the limestone before the ores were formed. Small grains have been observed in the midst of chalcocite and covellite, but they are of rare occurrence.

Sphalerite. A few large grains of sphalerite have been observed in several specimens but they yield no information concerning the relation of the mineral to the other sulphides. The sphalerite is earlier than the chalcocite, but apparently not readily replaced by it.

Galena. Only a few small specks of galena, doubtfully identified by microchemical tests, were observed.

Concentric and banded structures. Information concerning the mineral sequence presented on the preceding pages has been gained chiefly from certain peculiar knots in the mass of the monotonously uniform chalcocite, in which the rarer minerals of the deposit are concentrated. In the majority of these cases, the various sulphides possess remarkable concentric or banded structures, which, on account of their genetic significance are worthy of separate discussion. Chalcopyrite and bornite apparently form the ground mass, upon which most of the other sulphides have been built. The formation of the chalcopyrite and bornite was succeeded by the deposition of tennantite, both as a partial replacement of the earlier sulphides and as crystals apparently forming drusy coatings on the walls of small vugs. A later phase of the mineralization again produced chalcopyrite, closely followed by covellite in abundance with a little luzonite(?) and bornite. The chalcopyrite of the second generation forms rims about the tennantite crystals or cuts them in veins. It is most abundant, however, as a replacement of bornite, in complex aggregates of spines as previously described. The covellite is always abundant. It is prominent in large radial flakes in the centers of the concentic areas. From the relations to the crystalline tennantite bands, it is very probable that it constitutes the final filling of open spaces remaining in the earlier minerals, or else a replacement of other material with similar radial structure which had filled such cavities. There is, however, little evidence of any earlier mineral associated with the covellite in this form.

Elsewhere the covellite replaces bornite, and in places so thoroughly that little of the original sulphide remains. Here and there, small angular grains of chalcopyrite or of bornite occur between the covellite crystals. No clue is given as to their relative ages. They are probably contemporaneous, but it cannot be stated positively. A little bornite, in feeble veinlets is apparently formed at about the same time as the crystalline covellite. The veinlets cut chalcopyrite of both ages, and also the tennantite. The luzonite is in part contemporaneous and in part later than the crystalline covellite. It forms veins in the tennantite and covellite, but also occurs as sharp crystals, euhedral toward the covellite fields. In a few instances, fine rims of the luzonite were observed following the serrate outlines of the covellite blades. Chalcocite replaces all of the preceding minerals and structures. In some specimens, it is present only as veins or bands parallel to or breaking across the complex aggregate; in others, more extreme replacement has left only coarse sheaves of covellite (figures 128-129) or rings or bands of luzonite or of tennantite. Some traces of these minerals are always present in the pebbly chalcocite, or in the mammillary chalcocite, and it is very probable that these structures were inherited from such complex masses of earlier sulphides.

Enargite is rare in the knots of concentric sulphides. It is chiefly a direct replacement of the limestone, rather than an open space deposit or a replacement of other sulphides.

Oxidation. Distribution. The products of oxidation are prominent in all parts of the deposits. In no place, however, is the alteration of the original minerals complete, but, on the other hand, there are few places where no traces of oxidation exist. The degree of oxidation varies locally with changes in the ore minerals or wall rocks but, in general, it is surprisingly constant throughout the deposit.

Certain structural features, however, offer especially favorable conditions. Where cross-breaks of post-mineral age intersect the veins, the alteration is found to be most intense. Bedding planes and the fractures along which the ore has been localized also afford channel ways for descending solutions; in the Jumbo mine, for example, the upper surface of the zone of the flat fault is a particularly favored locus for oxidation, but it is less marked in the Bonanza Mine. In general, the cross-breaks, which allow unaltered surface solutions to descend to great depths through barren and chemically stable limestone, are more important agents in promoting oxidation than the breaks parallel to the ore, for in these, later solutions descending from the surface are quickly robbed

of their powers of oxidation by the easily altered sulphides in the upper parts of the deposit. Throughout the massive sulphide-ores, the alteration is confined to the surfaces of joints or small cracks, or to the walls of vugs. The alteration, however, is feeble; it is rarely pervasive, and only where an isolated chalcocite stringer happens to be attacked, does it approach completion. Nevertheless, the oxidized copper minerals in the aggregate form a sufficient fraction of the ore to have warranted the building of a special plant for their treatment by an ammonia leaching process.

The sulphides are exposed on the present surface, and show no greater alteration there than in the deepest workings. Broad faces of chalcocite, broken by the mechanical disintegration of the cliffs, have not developed more than a tarnish from their exposure to the air. At the Bonanza Mine, the disintegration of the vein has enriched the talus and the small glacier below it to such an extent that the ice and broken rock constitute a good ore. This persistence of sulphides in loose material, exposed as favorably as possible to the influence of oxidation, illustrates forcibly the negligible extent of surficial decomposition under present climatic conditions.

Underground Temperatures.- The mine temperatures do not rise above the freezing point of water at any time of year, except in a few places on the upper levels where the ventilation is good, or in confined drifts where many men are working. The mines are therefore absolutely dry, even on the lowest levels. Ice is a common mineral, occuring as splendid frost crystals on the walls of drifts near the surface, and as partial or complete fillings of fissures or other cavities at all depths. There is no circulation of water at present, consequently no oxidation is possible except by cold dry air, which is negligible.

Water Level.- There is no indication of a frozen groundwater level. The continuation of abundant oxidation to the bottoms of the mines indicates that under earlier conditions, the water level was below the deepest workings developed at present, which are more than 1000 ft. below the crest of the ridge above the Bonanza and Jumbo Mines. This deep oxidation indicates almost certainly that the topography preceeding the present glacial period was one of marked relief, and therefore of active erosion. The alteration of the sulphides was checked by the increasing aridity due to the glacial climate, and the various phases of the oxidation have been preserved with unusual completeness.

Minerals due to Oxidation. - The minerals, obviously formed by oxidizing processes, are as follows; (1) malachite, (2) limonite, (3) covellite, (4) antlerite, (5) azurite, (6)

arsenates of copper, (7) chalcanthite and (8) cuprite. They are listed in the probable order of their abundance. Some quartz in the antlerite may be due to oxidation.

Malachite is the commonest product of oxidation. It is abundant as a replacement of chalcocite, or as cavity fillings in vugs or other open spaces. As has been described, it penetrates the chalcocite in veinlets, whose orientation is controlled by the structure of the sulphide, producing lattice patterns, or scalloped bands in the material with the concentric structure. It is also a replacement of limestone to a slight extent. Coarse crystals of calcite with malachite developed along their cleavages were observed. Malachite produced in this way is far less abundant than that which has replaced chalcocite or the other sulphides directly.

Azurite is closely related to the malachite in origin. It is unusually abundant in proportion to malachite in the Kennecott ores. Vugs in the chalcocite lined with azurite crystals are very common, and in nearly all places where malachite is developed, there is some azurite formed with it. No definite age sequence between the two carbonates could be established however. In some places one would be the older, in others the reverse would be true. There is a slight tendency for the ratio of azurite to malachite to increase in the heart of massive ore-bodies, and to decrease in the zones of more intense oxidation.

Limonite is widely distributed throughout the deposits. It is most intensely developed in close association with the sulphides. Stains penetrate the limestone or are diffused through gouge for notable distances, but the percentage of iron is much lower than in material adjacent to the ore. Pure massive limonite is rare however. It is nearly always mixed with malachite or azurite, or else with residual limey material.

The abundance of the limonite is surprising when the low iron content of the ore is considered. In the largest chalcocite masses, as in the Jumbo Mine, where there is almost no iron, limonite is least abundant; in the few places where bornite and chalcopyrite were found, limonitic alteration is very prominent. This relation suggests that the limonite is derived directly from residual iron-bearing sulphides in the chalcocite, but the distribution of abundant limonite is by no means limited to the places where the iron-rich sulphides are present.

As has been stated, no gossan remains at the present surface. Limonite is as plentiful in the deepest levels as in the shallow parts of the ore.

Covellite is the first product of the oxidation of chalcocite at Kennecott. Its relation to the chalcocite is conclusively shown by the field associations and confirmed by its distribution along malachite veinlets ob-

served under the microscope. Zones of chalcocite partially altered to covellite exist between unaltered chalcocite on one side and oxidized minerals on the other. Under the microscope, rosettes and sheaves of covellite commonly accompany malachite veinlets in chalcocite (Fig. 103). The spots of covellite, spreading out from the channel-ways, resemble the products of decay advancing into wood. It is usually closely followed by the carbonates, and there can be little doubt that they are successive products of the same general processes.

Antlerite and Chalcanthite are associated with secondary covellite in a remarkable ore-body in the Jumbo Mine. A large, roughly pipe-shaped mass of oxidized ore occurs parallel to the dip of the bedding at base of one of the large sulphide stopes. The overlying chalcocite is the pure, crystalline type common in the Jumbo Mine. It passes without sharp boundary into a purplish friable material, resembling covellite, but porous and with a low specific gravity. In the intermediate zone between the two extremes, chalcanthite occurs in an intermittant band of 1/2 to 1 inch in thickness. From the results of chemical studies on this material by Dr. E. T. Allen and Dr. H. E. Merwin of the Geophysical Labratory, the following information was sent us:- The composition of the covellitic material is:-

"Cu S	50.44 per cent
Cu S O_4. $5H_2O$	45.20
Quartz	4.56
	100.20 per cent

The quartz crystals are all well formed and each is doubly terminated. The 45% copper sulphate was a surprise as it was not detected under the microscope. Each grain of covellite is very minute and is probably surrounded by a zone of sulphate". [1]

The presence of the quartz was not suspected. The overlying chalcocite contains practically none, consequently it may have been introduced with the oxidizing solutions.

In the field the covellite can be detected cutting the chalcocite in a net-work of fine veinlets. The material is very difficult to polish, but even on imperfect surfaces, the relation to chalcocite was clear. The covellite is without question a replacement of chalcocite.

That the reacting solutions contained copper sulphate is indicated by the presence of the chalcanthite. Chalcanthite, however, is very uncommon under normally humid conditions, and its formation here must be attributed to the increasing aridity at the beginning of the glacial period.

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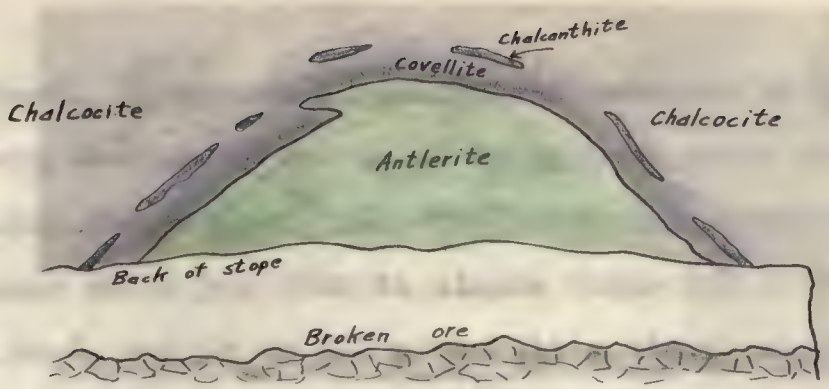
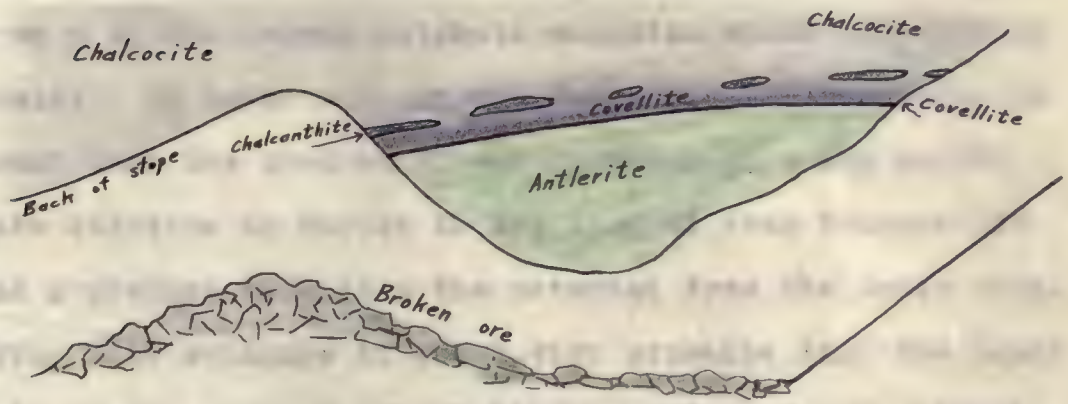
1. E. T. Allen, Private communication to L. C. Graton, Jan. 1916.



Transverse section

Scale :-
10 feet



Longitudinal section

Fig. 37. Chalcocite-covellite-antlerite ore-body, Jumbo Mine.

The zone of covellitic material which is a foot or so in width, forms a rim around an underlying larger mass of light greenish material, which in the field we believed was malachite contaminated with sulphates. The boundary between the covellite and this oxidized product is fairly sharp, but fine stringers of the sulphide extend in lacy masses several feet from the

line of contact. Specimens of the purest material which we collected were studied by Dr. E. T. Allen, who wrote as follows concerning the mineral[1]: - "The particular basic sulphate of copper which you find in Alaska turns out to be 3 Cu O. SO_3 $2H_2O$, and is in all probability identical with antlerite which is in turn identical with stelznerite. It is very difficultly soluble. I am inclined to connect its formation with the presence of limestone.....Of course, basic copper sulphate is formed by the action of water on a dilute copper sulphate solution which contains no free acid." In later work in the Geophysical Laboratory, it was found that the product of the reaction of a 10% cupric sulphate solution on marble in the lump at room temperature yielded a product much like the material from the Jumbo Mine.

From this evidence it seems very probable that the basic sulphate is the product of solutionscarrying copper sulphate reacting with the underlying limestone. The field relations are in accord with this interpretation. The lace work of covellite veinlets may be residues of chalcocite veinlets in original limestone. Very similar conditions have been observed on the edges of unaltered chalcocite ore-bodies.

Cuprite is very rare in the deposits in the limestone. One little nest of octahedra coated with malachite was found

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1. Private communicate to L. C. Graton.

1. Cited in p. 5, Erwin.

in the Bonanza Mine, but the mineral was not observed elsewhere except in small amounts under the microscope. The common occurrence of cuprite associated with native copper, described in connection with the greenstone deposits, offers an interesting contrast, and indicates the control of wall rock on the character of the oxidation. Native copper has not been observed in the deposits in the limestone.

Arsenates of copper are formed in small quantities by the oxidation of the enargite-bearing ore. They are in most cases mixed with malachite, and have not been identified mineralogically. Mixtures of enargite and chalcocite have been observed to oxidize more readily than the pure enargite. The chalcocite is apparently the more resistant.

The influence of oxidation on the wall-rock is manifested chiefly by the replacement of calcite or of dolomite by copper carbonates, basic sulphates, or limonite respectively. The limestone being inert to simple oxidation shows no traces of descending solutions away from the ore except veins of calcite or dolomite in coarser crystals than the grain of the rock. However, near the ore, especially where the development of limonite is most intense, the limestone is altered to a sandy, incoherent material, apparently by the partial leaching of the rock, which is ~~not~~ readily attributed to the attack of the acid, produced by oxidation of the sulphide or the hydrolization of the ferric sulphate which produced the limonite.

This is especially noticable in the Jumbo Mine near where pyrite was found and on the under side of sulphide masses.

THE ORIGIN OF THE COPPER DEPOSITS IN THE GREENSTONE.

Similarity to Other Regions. - The mineralization in the greenstone is similar in many important features to that described in numerous widely separated regions where copper minerals occur in basic lavas.[1] The forms assumed (veins of rather slight persistence, disseminations, and amygdule fillings) the metallic minerals (bornite, chalcopyrite, native copper and cuprite) and the gangue minerals (calcite, quartz, epidote, chlorite and - although not abundant - zeolites, datolite and prehenite) are all characteristic of this world-wide type of mineralization.

Source of the Metal. - The distribution of the copper through all parts of the Copper River region where the greenstones occur, supported by the common association of copper with basic extrusives elsewhere, points definitely to the lavas themselves as the source of the metal. Lindgren writes:[2] "Basic igneous rocks such as gabbro, diabase, basalt,

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1. Lake Superior region; White River District, Alaska; eastern Oregon (20 miles west of Baker City); Triassic Traps of New Jersey and Conn.; near Lurray, Va.; South Mt., Pa.; the Bay of Fundy, Nova Scotia, the Faeroer, north of Scotland; Sterling in Scotland; Oberstein a.d. Nabe, Germany; Sao Paulo, Brazil; the Kristiania Region, Norway; New Guinea; the Transbaikalian provinces on the Dochida River; Monte Catini, near Livorno, Italy. (For a general discussion and references to literature of the above districts see Lindgren's Mineral Deposits, p. 392.)

2. Mineral Deposits, (Mc Graw-Hill, New York, 1913), p. 393.

some andesites and basaltic flows designated melaphyres or amygdaloids probably always contain copper, in some cases as much as 0.1 or 0.2 per cent., but commonly about 0.02 per cent. of the metal. According to Volney Lewis and F. F. Grout, the copper is present as a silicate possibly in part as a sulphide such as bornite or chalcocite-" In the Kennecott district, chalcopyrite has been observed as an accessory mineral in the lavas[1] apparently remote from notable mineralization, and in all probability the sulphide is a primary constituent of the rock. No analyses of the greenstone have been made however, but the general distribution of copper is shown by the commonness of faint stains of malachite in fractures along which waters have percolated.

Theories of Concentration of the Copper in Basic Lavas. Although most writers are in general agreement in regarding the basaltic lavas as the source of the copper, there is considerable difference of opinion concerning the mechanism by which the concentration of the metallic mineral was effected. Whitney, Pumpelly and Wadsworth have attributed similar ores in the Lake Superior region to concentration and deposition by descending waters. Van Hise regards the

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1. Moffit and Capps, Loc. cit.

1. Smith and Jones, loc. cit.

zeolites, which are usually closely associated with the copper minerals, to be products of descending surface waters or similar percolating waters in the zone of cementation, the material for the zeolitization having been extracted from the rock itself[1], although he somewhat later attributes the Lake Superior copper deposits to ascending solutions. Weed[2] believes ores associated with basic lavas in the Appalachian region in Virginia and Pennsylvania to have been formed by infiltrations from the surface. According to a theory advanced by Lane[3] for the Lake Superior deposits, the lavas are believed to be submarine effusions, and the concentration of the copper is attributed to the action of heated sea water on the beds. Zeolitic deposits in the Watchung basalts, in which a little copper occurs, are believed by C. N. Fenner[4] to be the result of lava flows encountering water in shallow lakes or playas. The changes effected are attributed to readjustments of the mineral combinations along fractures and in the rock itself

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1. C. R. Van Hise, Monograph 47, U.S.G.S., 1904, pp 333 and 633.
2. W. H. Weed, Types of copper deposits in the southern United States - T.A.I.M.E., Vol. 30, 1900, pp. 449 - 504.
3. A. C. Lane, Salt Water in the Lake mines, Proc., Lake Superior Min. Inst, vol. 12, 1906.
4. C. N. Fenner, The Watchung basalt and the paragenesis of its zeolites, Annals., N. Y. Acad. Sci., vol. 20, part 2, pp. 97 - 187, 1910.

under the influence of steam and hot waters. Lewis[1] assumes hot solutions of cuprous sulphate released from intrusive trap magma to account for native copper in certain other New Jersey deposits. In the region about the headwaters of the White River, Alaska, chalcocite, native copper and a black hydrocarbon occur with calcite and various zeolites in amygdaloids, possibly of the same age as the Nikolai greenstone. The deposits are described by Adolph Knopf[2], and are attributed to hot solutions circulating through the lavas soon after their extrusion. The flows are believed to be submarine from fossil evidence in interbedded tuffs and breccias.

The development of albite, epidote, chlorite and datolite in certain of the veins in the Nikolai greenstone indicates that they are not the product of cold meteoric waters, for these minerals are not formed under such conditions. The later minerals, calcite and the zeolites, are undoubtedly the products of milder conditions, but probably part of the same sequence. Veins similar to those at the Erie Mine, which break across the greenstone-limestone contact can not be related to cooling effects of the lavas, and were without question formed under later and very different conditions. The shorter veins, throughout the formation, which rarely break through more than three

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1. J. V. Lewis, Geol. Sur. New Jersey, 1906, p. 131.
2. A. Knopf; Loc. cit.

[illegible]

or four flows, may be the products of the final stages of the vulcanism, but they are quite similar to the later veins. The information concerning the submarine or subaerial extrusion of the lava is too indefinite to base any theories upon. No evidence favoring a submarine origin was observed near Kennecott; the limonitic horizons suggest land surfaces, but do not prove it.

The intrusions of the porphyries in post-Jurassic time were wide-spread phenomena, and the unequal heating to which the country must have been subjected, undoubtedly accelerated the circulation of the ground-water. Heated solutions, traversing the copper-bearing rocks,are agents capable of causing noteworthy changes and may be the cause for some of the greenstone veins, such as those breaking the limestone-greenstone contact. The importance of this circulation and possible structural relations will be discussed more fully on the pages dealing with the origin of the ores in the limestone.

The long-continued volcanic activity in the Tertiary may have had a similar effect, but it was probably neither as localized nor as intense as the heating caused by the porphyry.

The ores on Nugget Creek in the Kuskulana District are stated to be later than important structural changes in the greenstone.[1] If so, they are not products of the cooling lavas, but must be attributed to later causes.

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1. A. Wandtke, Oral communication.

Porphyry intrusions are common in this region also, and may be the indirect agents, as discussed above. Certain ores in this district are closely related to the porphyry, and are probably contact effects, but their mineral character (pyrite, magnetite and chalcopyrite with garnet) is in striking contrast to the ores in the greenstone in general and argues strongly against the porphyry as the general source of the copper. The porphyry intrusions may have had an important part in the formation of the deposits, but it is not believed that they supplied the metal.

The chalcocite in the greenstone deposits is clearly secondary in part, and a replacement of bornite. Near Kennecott, chalcocite is only slightly developed in the greenstone. In the Kuskulana district, the chalcocite is of two ages. The older, which is more abundant, is either a primary intergrowth or a replacement of bornite. If it is of the latter origin, it may possibly be secondary and related to an older topography. The chalcocite of later age is due to feeble enrichment from a sur-

face of rapid degradation, probably of inter-glacial age.

Résumé. The source of the copper in these deposits is believed to be the lavas themselves; the concentration of the metal may have taken place in part by heated solutions as the lavas cooled, but it is probable that the stronger veins are of later origin, and were deposited by the circulation of solutions heated and set in motion by the intrusions of the post-Jurassic porphyry. The chalcocite is secondary in part, and a replacement of bornite. Chalcocite in graphic and similar structures in bornite from the Kuskulana District is possibly primary; the origin of chalcocite in these structures will be considered separately in a later section of the paper.

THE ORIGIN OF THE COPPER DEPOSITS IN THE LIMESTONE.

Summary of Significant Features From our observations in the field and in the laboratory, and from the results of work in the Geophysical Laboratory, many features concerning the ores in the limestone have been definitely established. The most important points which must be taken into consideration in any theory of origin for the deposits, are summarized in a following paragraph.

The first ten observations bear chiefly on the problems concerned with the primary origin of the deposits - the source of the copper, the manner of concentration, and its present loci. The question whether the chalcocite was formed directly as a replacement of limestone or a replacement of older sulphides depends largely on the observations listed from (11) through (17), while the problem of the secondary or primary origin of the chalcocite requires the consideration of the remaining points of the list as well.

The list of significant features is as follows:--

(1) The dependence of the ore on the greenstone-limestone contact (the Mother Lode deposit an apparent exception);

(2) the widespread distribution of copper in the underlying greenstone;

(3) the dependence of the ore on definite fractures, and the lack of disseminated sulphides;

(4) the definite lower limit (stratigraphically) of the ore in the larger mines;

(5) the gradual decrease in ore (chalcocite) passing upward, stratigraphically;

(6) the sulphides a replacement of limestone in nearly all places where the relation is shown;

(7) the occurrence of small knots in the ore characterized by the complex concentration of the less abundant minerals, and usually by concentric structures;

(8) the lack of alteration in the wall rock (except partial recrystallization);

(9) the occurrence of enargite in notable amounts in the Bonanza Mine;

(10) the lack of definite relations between the ore and any intrusive rock;

(11) the great size of the ore-bodies;

(12) the variation in texture of the chalcocite (steely and crystalline types);

(13) the dominance of chalcocite over other ore-minerals and its unusual purity;

(14) the results of analytic and synthetic work on Kennecott chalcocite by the Geophysical Laboratory; constantly low copper content and specific gravity of the chalcocite; chalcocite-covellite solid solutions; the high and low temperature forms of chalcocite;

(15) the replacement relations which the chalcocite exhibits toward all other sulphides (except a part of the covellite);

(16) the common distribution of traces of bornite throughout the chalcocite (most abundantly in the steely Bonanza glance, less abundantly in the crystalline Jumbo glance);

(17) the definite structural relations occasionally shown between the chalcocite and bornite;

(18) complete lack of surficial alteration under present climatic conditions;

(19) wide-spread but partial oxidation throughout the mines; lack of dependence on present surface, and lack of diminution with depth within the limits of the mines in 1916;

(20) the existence of physiographic conditions which afford land surfaces of possible relation to the secondary processes,- pre-glacial topography of notable relief; older Tertiary topography of gentle relief; pre-volcanic peneplain in early Tertiary, and pre-Kennecott post-Chitistone peneplain;

(21) the existence of structural features - low dip and flattening of limb of anticline to the southwest; the influence of the flat fault as a barrier for descending solutions;

(22) the slightly greater abundance of bornite in the chalcocite from the Erie Mine, at a lower elevation on the limb of the anticline than the Bonanza and Jumbo deposits;

(23) the occurrence of bornite, in slightly more abundant amounts, in the open-cut at the Bonanza Mine under the zone of the "flat-fault."

The Origin of the Primary Ore. The only possible sources of the copper as far as our knowledge of the district extends are the greenstones and the post-Jurassic porphrries. The remoteness of the Tertiary volcanics, and the lack of any known mineralization associated with them makes it extremely improbable that the copper was derived from any phase of their activity.

The close association between porphyry intrusions and ores in many of the copper camps in the Southwest suggests at the outset that similar relations may exist in this district. The porphyry, however, near Kennecott shows no traces of mineralization, either in the heart of the Porphyry Mt. stock or near the edges, or in the smaller bodies. At the Erie Mine, a three-foot dike cuts the vein, but it is unmineralized and most probably later than the ore, although this cannot be established with certainty. On the southwestern side of Porphyry Mt., low-grade gold ores have been found. Little information was available and the region was not visited. The gold is associated with pyrite, and the mineralization is apparently very different from that near Kennecott. In the Kuskulana region, a few deposits of little importance seem related to porphyry contacts; as has been mentioned the mineralization is in distinct contrast to that in the greenstone or in the limestone, and indicates a different origin from the larger deposits of the region.

There is the possibility that the ores were deposited from solutions which had emanated from the porphyry magma, but which had travelled some distance before depositing their load. The presence of enargite in the ore suggests an igneous source, but the confinement of the ores to definite fractures and the lack of silicification both indicate that the conditions of ore-formation were not intense. Nevertheless it is difficult to believe that emanations, even from a remote magma, would be so poor in silica and so relatively rich in the metals to have produced ore-bodies of the Kennecott type. At Bisbee, however, rich ores do occur in almost unaltered limestone in parts of the mineralized zone remote from the prophyry, yet there is little doubt that they were derived from the igneous rock. Consequently the possibility that the Kennecott ores were formed in this way can not be completely eliminated, although the probability that it is the correct view is not great.

The deposits in the limestone are believed by Moffit and Capps[1] and by J. D. Irving[2] to have been derived from the widely disseminated copper in the greenstone. It is suggested that the leaching of the limestone may have been facilitated by the heating due to the intrusions. "It is believed that the copper taken into solution by circulating water was carried into trunk channels and deposited there when the conditions were favorable..... Most frequently deposition took place

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1. Loc. cit.,(Bull. 448), pp. 81-83.
2. Loc. cit.

in the greenstone formation, but at times the copper-bearing waters passed outside the greenstone and into the overlying limestone before giving up their mineral load."[1]

The greenstone affords a competent source for the copper from a quantitative standpoint, for it is copper-bearing almost wherever exposed. Concentration of copper in the greenstone is known to have taken place in post-Chitistone time, for veinlets of the typical greenstone type break across the greenstone-limestone contact at the Erie Mine and elsewhere. The relation of the ores to the contact is striking in all cases except in the Mother Lode Mine. Even there it is not impossible that the ore may increase or at least continue until the contact is encountered. Small stringers of the chalcocite in the limestone are not infrequently encountered as one follows the contact along the cliffs between the Jumbo and Erie Mines. Definite fissuring is lacking in all these cases, however, and none of the seams persist many feet, but usually die out along bedding planes or short cross-fractures. The lower siliceous limestone beds are apparently unfavorable for mineralization. At the Jumbo and the Bonanza Mines the existence of strong and persistent fissures, both of the vertical zone and the flat fault, gave the ascending solutions access to the purer limestone, and also formed important channel ways in which a concentration could take place.

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1. Moffit and Capps, Loc. cit., p. 82.

It remains a disputed fact among geologists whether a metallic concentration of this sort can be effected by cold meteoric waters. However, ordinary meteoric waters undoubtedly become more active agents if accelerated both in circulation and chemical action by differential heating due to igneous intrusions. In the Kennecott district, the widespread intrusions of post-Jurassic porphyry probably had this effect. Where definite circulation along channel ways was established, copper leached from the greenstone would be precipitated, if conditions were favorable. Where these channelways crossed the contact, and the fissures persisted in the limestone, or encountered other dominant fractures, these conditions were supplied; where the limestone is unbroken, the mineralization rarely extends far above the greenstone.

The reactions involved in the solution and precipitation of the copper according to this theory of origin are not known. It is possible that the copper was transported in a colloidal state. Tolman and Clark[1] have shown that colloidal dispersions of copper sulphides may be induced by hydrogen sulphide, and flocculated by calcium carbonate. The existence of hydrogen sulphide in sufficient quantities in the greenstone, however, is a mere speculation. It or other agents could conceivably have been provided by emanations from the porphyry. The precipitation of the colloidal copper by calcium carbonate solutions offers an attractive explanation for the localization of the ores in the lower beds of the

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1. The dispersion and precipitation of copper sulphides from colloidal suspension, Econ. Geol., Vol. 9, p. 559-592, (1914).

limestone. The hypothesis finds possible support in the concentric and mammilary structures observed here and there in the ore, which resemble certain colloidal products, but from our present knowledge of colloids it is doubtful whether the great bodies of sulphides, clearly replacements of limestone could have been formed in this way.

The solutions deposited little except the metals, sulphur and arsenic. The quartz and silicates in the veins in the greenstone probably were derived from readjustments of material in the adjacent wall rock, with little transportation or addition involved, for these minerals cease abruptly at the limestone contact. It is possible, however, that the two rocks exert sufficiently different precipitation effects on the solutions to account for the changes.

In résumé, the theory of derivation of the copper by leaching of the greenstone offers a competent source for the metal and a satisfactory mechanism for its concentration, an explanation of the relation of the ores to the greenstone contact, and of the lack of silicification in the limestone. Its main points are supported by positive evidence. Opposed to it may be mentioned the lack of strong veins in the greenstone beneath the larger ore-bodies, and the occurrence of enargite in the limestone. The first objection is not vital; the material was not necessarily derived from the greenstone immediately below the contact, but may have migrated to the

favorable channelways in the limestone from notable distances. The occurrence of enargite is puzzling. At Butte it is regarded as a product of intense mineralization; here the conditions were undoubtedly relatively mild. No enargite was observed in the greenstone, and although the presence of small quantities of arsenic throughout the lavas is not impossible, its presence is a serious difficulty in the way of complete acceptance of the leaching theory.

THE NATURE OF THE CHALCOCITE.

Three possible explanations for the Kennecott chalcocite may be offered: (1) direct deposition from heated ascending solutions, as a direct replacement of the limestone, (2) a replacement of bornite and to a lesser extent of other sulphides by ascending solutions, or (3) a replacement of bornite and to a lesser extent of other sulphides by descending meteoric solutions. It must be admitted at the outset that the evidence is conflicting. In the final summary the weight given the various arguments will probably throw the scales one way or the other, but due to the different values given the evidence by several investigators interested in the problem, a close agreement is hardly to be expected.

Evidence from studies in the Geophysical Laboratory. In the course of work at the Geophysical Laboratory knowledge of certain properties of chalcocite was obtained which has a distinct bearing on the Kennecott problem.[1] Synthetic copper sul-

1 - E. Posnjak, E.T.Allen, and H.E.Merwin, Loc.cit.

phides formed under certain conditions were found to contain more sulphur than is demanded by the ratio 2 Cu : S. It was shown that these products were solid solutions of cuprous and cupric sulphide. Pure cuprous sulphide - chalcocite - was found to be dimorphous, the inversion temperature being at about 91°C.. Increasing the amount of cupric sulphide dissolved in the cuprous sulphide raises the inversion temperature. This takes place until cupric sulphide reaches a concentration of about 8 per cent, after which an inversion is no longer observed. The crystals of chalcocite formed at higher temperatures in various ways are isometric. When cooled below 91° C, inversion takes place, and if etched the characteristic etch-cleavage of orthorhombic chalcocite develops. Cuprous sulphide, however, containing more than 8 per cent of cupric sulphide if formed above 91° C does not develop the characteristic etch-cleavage of orthorhombic chalcocite at lower temperatures, but retains an octahedral parting which etches out more or less clearly.

The octahedral parting of the artificial material yields patterns on the polished surface which are similar to the etch-structures of the Kennecott chalcocite (Fig.139). "It is further significant that analyzed samples of the Bonanza ore show about nine per cent of dissolved cupric sulphide, a quantity sufficient to prevent isometric crystals which may have been formed above 91° from going over into the orthorhombic form as the cooling progressed. Etched surfaces of some of the analyzed samples of this ore contain grains in irregular veins

which etch like chalcocite (orthorhombic) and are thus shown to be the low temperature form. They may have formed above 91° and contain too little cupric sulphide to prevent their inversion, or they may have formed below the temperature of inversion."[1] In examining material sent to the Geophysical Laboratory from our collections, H. E. Merwin found a number of twinned crystals in the chalcocite, which he believes from measurements of the angles to be octahedral twins of chalcocite. If his interpretation is correct, it is the first recognition of isometric chalcocite in nature.[2]

The possibility of chalcocite, with over 8 per cent cupric sulphide, when formed at ordinary temperatures, assuming the octahedral form, has not been positively eliminated. It is stated, however, in their paper that if solid solutions containing over 8 per cent of covellite could be crystallized at temperatures just below 91°, they would probably etch like ordinary chalcocite.

From the work of the Geophysical Laboratory a fairly strong case is presented for the thesis that the Kennecott chalcocite is of primary origin and formed at a temperature above 91° C, but as it will be shown later, the octahedral structure of the chalcocite may be explained in another way that does not demand a high temperature for its formation, which consequently weakens the force of their conclusions.

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1 - Eugene Posnjak, E.T.Allen, and H.E.Merwin, Loc.cit., p.527.

2 - E.T.Allen, Private communication.

Evidence that the chalcocite is a replacement of bornite.

Structures identical with the isometric patterns described above have been observed, however, in chalcocite which is clearly a replacement of bornite. They were first described by Graton and Murdoch[1] in 1913. The etch-cleavage in some of the chalcocite was believed by them to be inherited from bornite. It was definitely pointed out that such cleavage in secondary chalcocite could not in all cases be distinguished from the regular (isometric) cleavage which they believed to be characteristic of primary chalcocite.

In a more recent article on the etch-patterns of chalcocite, C. F. Tolman, Jr., comes to the same conclusion regarding the replacement origin of the chalcocite with the triangular or rectangular pattern, and in addition states positively that this pattern proves the chalcocite to be a replacement of an earlier mineral, generally of bornite. Material from the Bonanza Mine at Kennecott, and from the Apache Mines, Pima Co., Arizona, is described by him in which the derivation of chalcocite from bornite is clearly shown. The blue and white patterns on slightly tarnished polished surfaces are regarded by Tolman as certain proof of replacement origin. It is believed "that the color is due to the unmixing of the solid solution [of chalcocite and covellite] which develops sub-

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1 - L.C.Graton and J.Murdoch, Loc.cit.

2 - Loc.cit.

microscopic crystals of covellite." White chalcocite of later age is described, which is believed to be due to supergene action, preceding the development of covellite and malachite. Tolman summarizes the paragenesis of the ore minerals of the Bonanza deposit as follows:-"First group of minerals:-Bornite, klaprothite klaprotholite, and galena; temperature of formation probably relatively high for copper deposits, as Prof.Rogers has found klaprothite, bornite and chalcocite to be grouped together in most of the chalcocite deposits thought to have been formed by ascending solutions, and at temperatures above those at which downward enrichment takes place. Second group of minerals:-Blue and white chalcocite of the first generation, secondary after bornite. The temperatures governing, and the source of the solution causing this alteration, are unknown. Third group of minerals.- This includes a set of minerals formed progressively under conditions of increasing oxidation and represented as follows: Second generation of white chalcocite → (covellite and chalcopyrite) → tenorite (and cuprite) → malachite → azurite. The group is formed at about 0°C., as much of the ore is frozen throughout the year. It is the result of the present vadose circulation, and the copper is migrating chiefly as malachite."

The mineral sequence given by Tolman is confirmed, in a general way, by our work; but from field observations and larger collections our mineral list is considerably greater. No klaprotholite was observed, however, and the rarity of galena hardly

entitles it to be mentioned with bornite. Tolman's statement of the temperature of formation of the primary ore is based on little real evidence. In his third group of minerals, we can not confirm the occurrence of tenorite. Limonite is not mentioned, although it is an extremely abundant mineral. It is doubtful if azurite can in general be regarded as a replacement of malachite. Copper migrating as malachite by means of a frozen vadose circulation is rather surprising.

To return more definitely to the topic under discussion, there is good evidence that an important part of the chalcocite at Kennecott is a replacement of bornite. The fine grains of bornite, common in many parts of the ore, are most simply interpreted as residues. When they are of sufficient size, replacement relations are usually shown. The triangular pattern in the chalcocite is similar to the structure remaining after a lattice replacement of bornite. The distributinn of bornite specks and spines in a few specimens lends force to this interpretation for the origin of part of the Kennecott chalcocite.

If the chalcocite is a replacement of bornite two origins are possible; (1) it is the final product of the ascending primary solutions, or (2) it is a product of descending meteoric solutions.

Secondary versus Primary origin for the Chalcocite. It is obvious that secondary enrichment is virtually impossible under the present climatic conditions at Kennecott. It is also unlikely that enrichment of any importance was associated with

the oxidation now prominent throughout the deposit. The oxidation is not intensive and is limited to fractures for the most part upon which the chalcocite shows no dependence. The topography and climate immediately preceding the present glacial epoch probably supplied the necessary conditions for its development. From the evidence presented by Capps,[1] two glacial periods seem probable; the oxidation is possibly the product of the inter-glacial period.

The various surfaces to which secondary ores could be related have been described in detail on pages 227-234. The most recent is the surface of low relief developed during the period of pre-glacial erosion, which to judge from remnants could not have been far above the mines. During this time the ores may well have been exposed to long continued oxidizing influences in so permeable a medium as the Chitistone limestone. The long period of erosion which produced the even surface beneath the Tertiary lavas could also have afforded favorable conditions for enrichment. If projected, this surface would pass not far above the top of Bonanza Peak. The peneplain cut across the Chitistone limestone and the greenstone, which serves as a floor for the Jurassic sediments, may likewise have offered a surface from which enrichment could take place if the ores were then in existence. At a point less than two miles from the mines, the erosion at this time was sufficient to strip the limestones com-

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1 - S. R. Capps, Loc.cit.

pletely from the greenstone. Although it is not possible to determine the actual relation of these surfaces with greater precision, it is evident that there were at various periods physiographic conditions which may have permitted enrichment on an important scale.

Structural conditions at the Jumbo, Bonanza and Erie Mines are such that a small amount of erosion would make a large amount of copper available for enriching solutions. The plunge of the ore-bodies is approximately parallel to the dip of the limestone. There is good evidence that the dip flat-

Fig. 38 . Sketch illustrating relation of ore to successive erosion surfaces.

tens to the southwest as the crest of the anticline is approached. Consequently the ores which have been eroded probably had a lower dip than those remaining. If a 30° dip is assumed, which is the least favorable case, it is evident that

if the surface is lowered 100 feet, 200 feet of the ore measured along the dip would be removed. With a decreasing dip this ratio would increase. The concentration of the descending solutions laterally upon the underlying ores would be efficiently effected by the barrier offered by the gouge layer of the flat-fault. These factors, in addition to the well-known ease with which oxidation penetrates to great depth in limestone, offer unusually favorable conditions for the concentration of copper by descending solutions.

The occurrence of a slightly greater amount of bornite in some of the chalcocite from the Erie Mine than is commonly found in the Kennecott ores, is a slight argument favoring a secondary origin, for the Erie Mine is farther down the limb of the anticline and its ores would have been farther below the older surfaces to which the enrichment must have been related than is the case in the other deposits of the district.

In the summer of 1916, some chalcocite with unusually abundant bornite was encountered in the open-cut of the Bonanza Mine, at a horizon below the zone of the flat-fault. The bornite is in material which is undoubtedly more resistant to percolating solutions than the overlying rock, and its preservation in such places is quite in agreement with the relations expected under the conditions of the hypothesis of secondary origin for the chalcocite.

The ease of bornite enrichment is another factor worthy of

note in favor of a secondary origin for the chalcocite. The presence of chalcocite of unquestioned secondary origin in the bornite nodule from the limestone near the Erie Mine shows that the enrichment can take place in the presence of calcium carbonate, although the alteration in this case is on a small scale.

Opposed to the secondary origin of the chalcocite are the following arguments:

The chalcocite occurs in limestone which for the most part shows no traces of acid attack. Although the enrichment of bornite produces comparatively little acid, the great quantities involved if all the chalcocite were formed in this way would surely seem to have been sufficient to have had a pronounced effect on the wall rock. It should be pointed out in this connection, however, that according to the equation established by Zies[illegible], Allen and Merwin[1], bornite may alter to a mixture of chalcocite and covellite, as follows:

$$Cu_5 Fe S_4 + Cu SO_4 = 2 Cu_2 S + 2Cu S + Fe SO_4$$

with the production of no sulphuric acid. The analyses of apparently homogeneous chalcocite from the Kennecott deposits are uniformly low in copper, and are interpreted by Dr. Allen to indicate about 9 per cent of dissolved cupric sulphide. In addition there is a small amount of free covellite distributed rather generally through the ore. This total, however, does not yield the ratio demanded by the equation, but it is sufficient to reduce the amount of acid produced by approximately a quarter.

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1 - Loc. cit., p. 481.

The only evidence of acid attack is the sandy limestone, which was observed in a few places near the ore, some of which was associated with abundant limonite, and certain peculiar irregular masses of gouge-like material of uncertain origin. The former may be attributed as well to the acid released by the hydrolyzing of the ferric sulphate. To what extent the greater insolubility of the dolomite would influence its behavior toward acid attack is unknown.

If the chalcocite is attributed to the action of descending waters, it implies the movement of larger quantities of copper sulphate solution through the ore, and necessarily through the adjacent limestone. It has been established from both chemical and geological data that carbonates or basic sulphates of copper tend to form under such conditions, which would remove copper from solution and hinder the formation of secondary sulphides. It is evident that this process would probably be of little influence on solutions descending through the rich sulphide ores, but it would be expected to check the development of chalcocite in fine stringers in unaltered limestone. The occurrence of chalcocite in thin veinlets in calcite or dolomite, a few of which show no traces of malachite, azurite or sulphates, is a strong argument against the formation of the chalcocite from descending copper sulphate solutions.

The replacement of such large masses of bornite would involve the removal of a great quantity of iron, probably as fer-

rous sulphate. In neutral solutions, such as those in a carbonate rock, limonite would form readily if mild oxidizing conditions were encountered; if the iron remained in the ferrous condition reaction with the wall-rock might be expected to yield siderite. Important masses of siderite believed to be of similar origin occur at Bisbee. The limonite in the deposits is not as abundant as would be expected if the chalcocite were entirely a replacement of bornite under secondary conditions. The distribution of limonite in part suggests that it is a product of later oxidizing conditions and not of those which produced the chalcocite. Siderite has not been observed, and it is certainly not present in any noteworthy amount on the levels now exposed. These observations offer definite objections to any genetic process which would involve the transportation of large quantities of iron through the limestone in the form of soluble sulphates.

Passing upward perpendicularly to the stratification, the chalcocite in the veins gradually pinches out. The fissures continue and are usually marked by recrystallized limestone along their walls. The chalcocite in the upper beds cannot be said to be more intensely oxidized than that in the lower, and there is no overlying zone of oxidized ore. It is improbable, therefore, that the chalcocite could have been formed by vertically descending waters, for there are no known higher sources from which the copper could have been derived. If secondary, the copper along the upper edge of the ore-bodies must have been de-

TABLE OF ARGUMENTS CONCERNING THE ORIGIN OF THE CHALCOCITE

<table>
<tr><th colspan="2">Arguments Favoring A Primary Origin</th><th>Arguments Favoring A Secondary Origin</th></tr>
<tr><th>By Replacement of Limestone</th><th colspan="2">By Replacement of Bornite</th></tr>
<tr><td>(1) Purity of large bodies of crystalline chalcocite.
(2) 8 per cent. of dissolved cupric sulphide in the chalcocite and the isometric structure of the chalcocite.
(3) Chalcocite in limestone and in coarse calcite crystals which show no trace of alteration.
(4) Lack of uniform distribution of alteration of wall-rock.</td><td colspan="2">Veins of chalcocite in bornite grains, indicating replacement origin in part.
Patterns and bornite residues in chalcocite similar to the last stages of bornite-chalcocite lattice patterns.
Triangular pattern of chalcocite symmetrical to bornite spines.
Microscopic bornite grains in many parts of the ore.</td></tr>
<tr><td colspan="2">Lack of products of copper sulphate attack on the wall-rock in amounts comparable with the development and distribution of the chalcocite.
Lack of evidence of sufficient acid attack.
Continuation of chalcocite into the upper beds of the limestone without change except decrease in abundance.</td><td rowspan="2">Exceptionally favorable physiographic and structural conditions for oxidation and concentration of descending solutions.
The ease of bornite alteration to chalcocite under secondary conditions.
Development of secondary chalcocite in bornite nodule near the Erie Mine.
The bornite in greater abundance at Erie and in the lower beds in the open-cut at Bonanza.</td></tr>
</table>

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rived by almost lateral movement. With a 30° dip it is conceivable that descending solutions following the horizon of the flat-fault could have spread far enough to have accomplished this change (Figure 35), but it does not seem probable that it could have been done with such searching completeness. On the whole, the continuation of pure chalcocite in small stringers into the upper beds is a strong argument against the hypothesis of secondary origin.

The arguments supporting the various hypotheses of the origin of the chalcocite are summarized in tabular form on page 306. It is apparent that it is difficult to settle the question definitely, but the evidence on the whole presents a stronger case for the view that the chalcocite is primary than that it is secondary. The arguments supporting the latter merely show that conditions favorable for deep enrichment exist; they do not meet the detailed objections raised against it. It is certain that part of the chalcocite at Kennecott is a replacement of bornite; the possibility that some of the chalcocite may be a direct replacement of limestone at temperatures above 91° C., however, cannot be eliminated.

SUMMARY AND CONCLUSIONS.

The mineral deposits at Kennecott consist of two distinct types: (1) small but numerous bornite and chalcopyrite deposits of little commercial importance in the Nikolai greenstone, and (2) large ore-bodies of chalcocite in the Chitistone limestone.

The basic lavas, now greenstones, are believed to have been the source of the copper in both types. In the deposits in the greenstones themselves, the copper may have been concentrated in part by volcanic after-effects, but the larger veins were produced by later circulation of heated solutions. It is suggested that the solutions may have been derived from meteoric waters, accelerated in circulation and chemical action by the heat of the extensive post-Jurassic intrusions.

The ores in the limestone are also believed to have been formed by similar solutions, which had derived their copper content from the greenstone. Where fractures extended into the limestone, and other structural conditions were favorable, the solutions broke across the contact from the greenstone, and deposited the primary sulphides of the great ore-bodies.

The primary sulphides in the limestone were formed chiefly as replacements along the fractures, and never occur disseminated through the rock. Locally, deposits were made in small open spaces. The conditions of temperature and pressure were probably mild. The only rock-alteration is a partial recrystallization of the carbonates of the limestone. No silicates and a very subordinate amount of quartz occur in the ores.

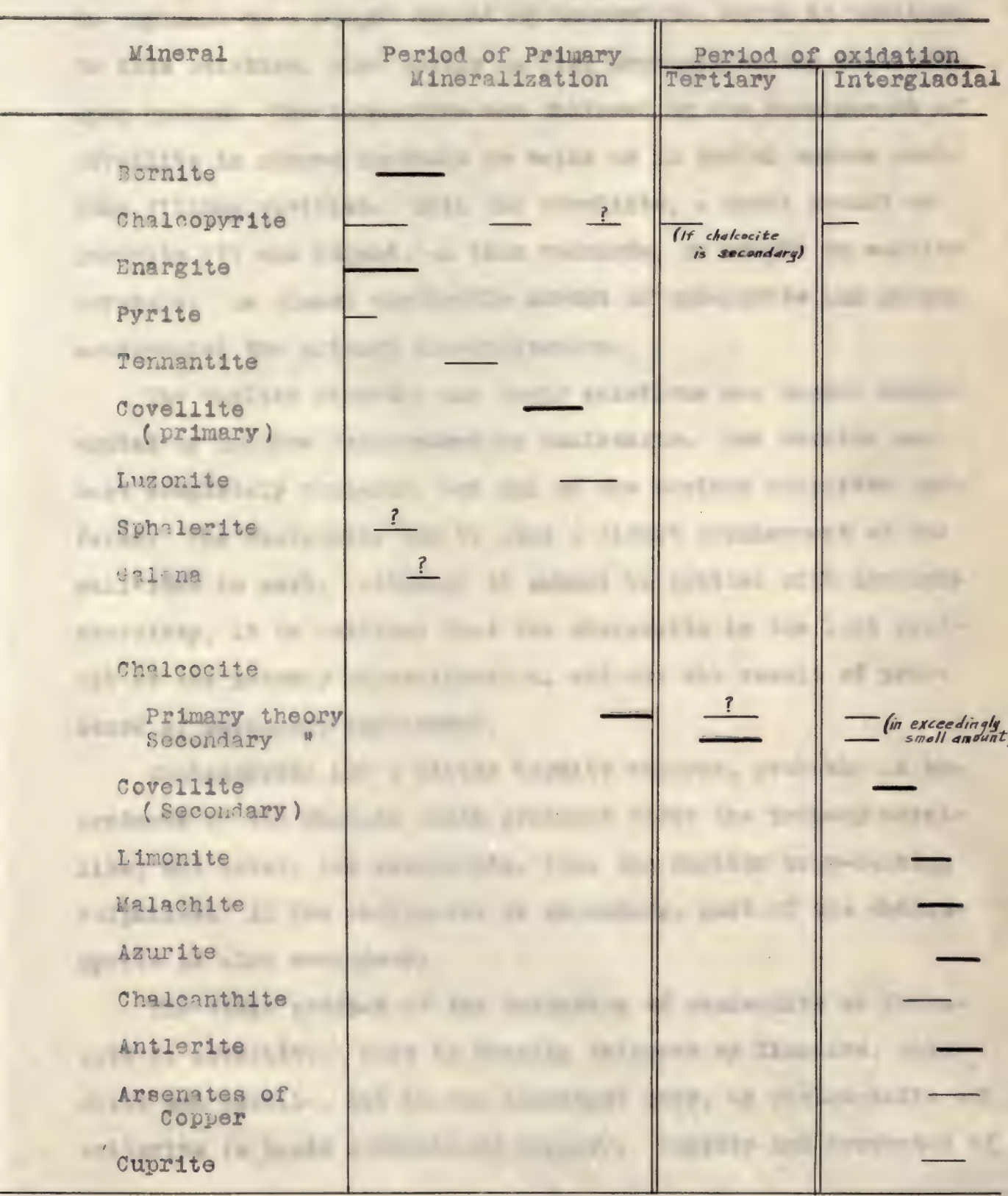
The list of ore-minerals and a diagram of sequence are given on page 309. Bornite, enargite and part of the chalcopyrite were the earliest ore-minerals to form. The bornite probably continued to be deposited somewhat longer than the chalcopyrite, but the two minerals are believed to have been essentially contemporaneous.

To follow page 310

copper occur, but are not common. A small amount of chalcocite, for example that in the bornite nodule near the Erie Mine, may be attributed to the period in which the malachite and limonite were developed, but it is almost negligible in quantity. The oxidation is not related to the present surface or to the present climate; it took place under pre-glacial, or possibly interglacial, conditions, when the climate was milder, and the relief somewhat like that at present.

If the mineralization continues with depth, there is little possibility that there will be notable decrease in the richness of the copper minerals. If the chalcocite is primary, little change would be expected; if secondary, it can be a replacement only of bornite, hence the change to primary ore would be a gradual one and not marked by serious diminution in copper values.

Diagram of Mineral Sequence.



Bornite was probably by far the most abundant. The chalcopyrite is replaced to a slight extent by tennantite, which in addition to this relation, also occurs as fine crystals on the walls of open-spaces. The tennantite was followed by the development of covellite in coarse crystals in veins or in radial masses probably filling cavities. With the covellite, a small amount of luzonite (?) was formed, as thin veinlets, or crusts on earlier crystals. An almost negligible amount of sphalerite and galena accompanied the primary mineralization.

The earlier minerals and their relations are almost obliterated by intense replacement by chalcocite. The bornite was most completely replaced, but all of the earlier sulphides suffered. The chalcocite may be also a direct replacement of the wall-rock in part. Although it cannot be settled with absolute certainty, it is believed that the chalcocite is the last product of the primary mineralization, and not the result of processes of secondary enrichment.

Chalcopyrite and a little bornite reoccur, probably as by-products of the changes which produced first the primary covellite, and later, the chalcocite, from the earlier iron-bearing sulphides. If the chalcocite is secondary, part of the chalcopyrite is also secondary.

The first product of the oxidation of chalcocite at Kennecott is covellite. This is usually followed by limonite, malachite and azurite, but in one important case, by chalcanthite and antlerite (a basic sulphate of copper). Cuprite and arsenates of

PART IV

GENERAL DISCUSSION

PART IV

GENERAL DISCUSSION

GENERAL FEATURES OF BORNITE DEPOSITION

Bornite in Deposits of Magmatic or Pneumatolytic Origin

Some Properties of Magmatic Sulphide Ores.[1] Magmatic sulphide ores are commonly regarded as those in which the sulphide minerals were formed directly from a magma in a manner analogous to the crystallization of the rock minerals. The ores should possess the structure of the igneous rock with which they are associated, and form an integral part of its body. The gangue-minerals of such deposits should be the characteristic minerals of igneous rocks. Alteration products such as garnet, wollastonite or tremolite, and especially those of hydrothermal origin such as epidote, sericite, chlorite, carbonates or zeolites should be either absent or of later origin than the sulphides.

Sulphides in many pegmatite dikes usually possess the properties mentioned above as essential characteristics of magmatic deposits. In most of these cases, however, there is reason to believe that the concentration of volitale constituents was greater than in a normal magma and that the deposition of the sulphides was related to these agents. Consequently for the sake of completeness in classification,

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1. Compare Lindgren, Mineral Deposits, p. 735.

List of

Original Documents

Showing Practice of Monthly Declaration

Forms in Germany at Beginning of Twentieth Century

[illegible] Many-
[illegible] political ideas are commonly regarded as given in writ-
[illegible] religious writers have formed distinctly from a study is
[illegible] another manifestation of the same ten-
[illegible]dency. The term economic imperialism has appeared of the [illegible]
[illegible] with which they are associated, but often to interpret
[illegible] of the body. The [illegible]-ultimately it must [illegible]
[illegible] the characteristic philosophy of [illegible] rooted.
[illegible] problems arise as matter, militarists of investing,
[illegible] especially those of [illegible] which we criticize,
[illegible], economic, movements of politics should be either
[illegible] or at least [illegible] as motives.

Following is best [illegible] since family possess
the [illegible] monitoring which an essential [illegible]
of economic [illegible]. It must of [illegible] manner, however, [illegible]
is remote it [illegible] case the [illegible] it [illegible] be-
[illegible] one [illegible] than [illegible] [illegible] and [illegible]
[illegible] of [illegible] [illegible] to [illegible].
Unfortunately for the [illegible] [illegible] [illegible] classification.

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1. Thomas Hodgkin, Political Imperialism, p. 127.

it seems proper to regard the origin of such deposits as pneumatolytic rather than directly magmatic. The two groups, however, are closely associated, and no sharp line can be drawn between them, for it is probable that pneumatolytic action plays a more or less important part even in those bornite ores which are most closely related to magmatic conditions. With changes toward milder pressures and temperatures, a similar gradation may exist between pneumatolytic and hydrothermal ores, but the point at which minerals of generally recognized hydrothermal origin appear may be established as the point at which true pneumatolytic conditions commence to give way to hydrothermal conditions.

Pyrrhotite-Chalcopyrite-Bornite Ores. The ores near Ookiep, Little Namaqualand, are the only magmatic deposits of the pyrrhotite-chalcopyrite type, in which bornite is an important mineral. The distribution of the ore-bodies in broad lenses or schliers in unusual basic rocks, which exhibit a remarkable degree of differentiation, suggests that the sulphides were derived directly from the magma. The sequence of the sulphides and their relations to the rock silicates indicate, however, that metasomatic replacement also played an important rôle in their formation.

From the experiments by Vogt,[1] it is very prob-

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1. L. J. H. L. Vogt, Die Silikatschmelzlosungen, pt. 1, Videnskabs-Selskabets. Skrifter, Math.-Naturv. Klasse, Kristiania, 1903, No. 8. W. Lindgren, Mineral Deposits, p. 761.

able that sulphides dissolved in a dry silicate melt would be the earliest constituent to separate out from a cooling solution. The late position of the sulphides in the sequence of gangue and ore-minerals is clearly out of harmony with these results, and indicates with certainty that different influences controlled the deposition of the sulphides in nature from those provided by the conditions of the experiments. Vogt suggests that the retention of mineralizers in the magma due to the great pressures, was probably the chief factor which determined the late position of the sulphides in magmatic ores. Concentration of metallic constituents is effected in residual portions of crystallizing magma, as is shown convincingly by ores in pegmatites and in high-temperature veins. In abnormal magmas in which a high metallic concentration had been produced by differentiation, this final segregation would probably produce a still richer and more fluid extract capable of migration and localization in definite ore-shoots. Such late magmatic solutions would be expected to corrode and replace the earlier silicates, and, as the character of the solutions changed, the earlier sulphides would become unstable and would be forced to yield to later products.

Such an explanation, which is offered for the Ookiep ores, may also harmonize the apparently conflicting field and microscopic evidence at Sudbury. The high metallic concentration of the magma in the lower portions of the

Sudbury basin may be attributed to direct differentiation in the liquid phase controlled by gravity, while the concentration of the sulphides into definite ore-shoots, with the accompanying replacement of the silicates and the successive ore-minerals, may be attributed to the agency of mineralizers in the final magmatic extracts. The importance of mineralizers in the magma is suggested by the presence of abundant micropegmatite throughout the overlying norite and granite. Tolman and Rogers[1] believe that the Sudbury ores are late magmatic products and claim to have reconciled the diametrically opposed views of origin. They state, however, that the ores were not formed by the sinking of the sulphide constituents, but offer no explanation for the concentration of the ores near the bottom of the magma chamber.

Lindgren[2] states that the temperature of formation of magmatic deposits proper ranges from 700°- 1500° C. He places the temperature of the magmatic ores associated with pegmatites at about 575°C. Tolman and Rogers,[3] however, emphasizing the replacement relations between the high temperature silicates and the sulphides, state that the formation of sulphides in all types of high-temperature deposits takes place probably not higher than 300°- 400°C. While the value of the work on temperature variations is

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1. Loc. cit.
2. Mineral Deposits, p. 188.
3. Loc. cit.

appreciated, it may be undesirable to try to express with too great exactness the temperature at which the sulphides in deposits of different types form. It seems reasonable to assume, however, that in deposits intimately related to igneous activity, there is a general decline in temperature from the initial conditions of the melt to the close of the mineralization. Though local or temporary reversals in this progressive cooling may be expected, the general tendency is probably sufficiently dominant to justify the assumption that the time relations of any mineral to the other products of the mineralization may be regarded as an approximate indication of the relative intensity of the temperature under which it was formed. In the deposits at Ookiep, where bornite is involved, the sulphides formed later than the rock-silicates (hypersthene, plagioclase, biotite), and consequently their temperature of formation may be assumed to be lower than that at which the silicates crystallized. The upper limit of the temperature of formation depends on the temperature of the crystallization of the rock minerals and is probably within the range set by Lindgren. There is no evidence which limits the temperatures in this case to the low values given by Tolman and Rogers, although the lateness of bornite in the sequence of silicates and ore-minerals suggests that it was formed at a considerably lower temperature than the latest rock-minerals.

Pneumatolytic Ores. In the remaining deposits

described in this group, the ores are of a somewhat different type, and clearly more dependent on pneumatolytic conditions. The sulphides occur in pegmatites or in other dike rocks in which numerous miarolitic cavities and the character of the associated minerals clearly indicate the importance of gaseous agents.

In the deposits at Copper Mt., La Fleur Mt., and at Engels, sulphides occur apparently as primary constituents of pegmatite dikes. In the first two deposits, bornite is the chief mineral in this association; at Engels chalcopyrite is more abundant in the pegmatites. At Evergreen the bornite is confined in a large measure to the dike in which the parent rock occurs, and this is also the case at La Fleur Mt. except where the syenite and syenite-pegmatite dikes cut gabbro. At Copper Mt. and at Engels, however, the disseminated sulphides in the plutonic rock constitute the chief ore-bodies.

In the pegmatites and in the parent dikes at Evergreen and La Fleur Mt., the sulphides are later than the silicates but there is almost no rock alteration connected with the mineralization, except changes attributable to pneumatolytic agencies, as the development of aegirite-augite and fluorite at Evergreen, or the tourmaline at Engels or Copper Mt. The ores in the plutonic rock at Engels, Copper Mt., and La Fleur Mt., on the other hand are usually accompanied by important changes, and are believed to have been deposited under a range of conditions, decreasing from the

intensity of the pneumatolytic stages through successively milder temperatures to the feebleness of final hydrothermal emanations. The formation of the sulphides in the wall rock was preceded by the development of hornblende over a wide zone at Engels, converting the original norite to the peculiar diorite or metanorite, but at Copper Mt. and La Fleur Mt. this change was more closely confined to seams. The sulphides soon followed, but were accompanied by an increasing amount of epidote, sericite and chlorite, indicating that the original pneumatolytic conditions had given way to hydrothermal. In the closing stages at Engels, the final effects are shown by the development of carbonates and zeolites. The association of the hydrothermal minerals with the sulphides is so marked in the disseminated ores at Engels and at Copper Mt., that these deposits are properly classed as ores of hydrothermal origin rather than pneumatolytic.

In all these deposits, however, it is fairly certain that the earliest formation of the bornite took place under pneumatolytic conditions. At Evergreen and La Fleur Mt., the chief mineralization was confined to this period but at Engels and Copper Mt., the formation of the sulphides continued and became of even greater importance under succeeding hydrothermal conditions.

The absence of pyrite in deposits of the magmatic-pneumatolytic type (including Ookiep) is noteworthy. Magnetite is usually abundant (except at Evergreen). In all cases it is the earliest ore-mineral, and indicates that the deposition of sulphur was unimportant in the early phases of the mineralization. The association of sulphur with the increasing copper suggests that it may have played an important part as a mineralizer.[1]

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1. Tolman and Rogers (loc. cit., p. 15, footnote 25) consider sulphur as a mineralizer of importance in the magmatic stage in this type of deposit.

The practical absence of pyrite and the dominance of magnetite in the early phases of the mineralization in these deposits may be interpreted as an indication either that sulphur was not present in notable concentrations at the start but was introduced later with the copper, or that the temperature preceding the deposition of the copper was above the dissociation point of pyrite. The dissociation-pressure curve of pyrite, recently established by Allen and Lombard[1] indicates that although pyrite is practically stable up to about 600°C., beyond that point the sulphur vapor pressure necessary to prevent the dissociation of pyrite increases very rapidly with the temperature. It suggests that if the dissociation interpretation is accepted, and if the conditions of the dissociation experiments may be applied directly to the conditions in nature, then the temperatures at which the magnetite formed were not below 700°C.

Bornite in Deposits of Contact-Metamorphic Origin

Bornite ores produced by contact-metamorphic action may be divided into two classes:

1. the ores associated with intense localized alteration of invaded sediments and intrusive along the contact; and

2. the ores associated with a widespread development of hydrothermal minerals such as epidote, chlorite, and sericite, in both the county rock and the igneous rock.

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1. A method for the Determination of Dissociation Pressures of sulphides and its application to covellite (CuS) and pyrite (FeS_2), A. J. S., Vol. 43, p. 193, (1917).

The ore-bodies of the first group, such as the Marble Bay, Whitehorse and Seven Devils deposits, are usually smaller, and may be considered of direct contact-metamorphic origin in the strictest usage of the word. The ores of the second group, which are of greater commercial importance, and are well illustrated by the extensive deposits at Bisbee, seem to be the product of milder conditions that may extend farther from the igneous mass and in which contact-metamorphic conditions may grade without break into hydrothermal. The source of the metals is clearly the intrusive rock in both cases, but in the latter the distribution of the ores is likely to be less closely related to the actual contact than in the former.

In the three deposits of the first type which have been studied, bornite is the chief ore-mineral, but in each it is associated with almost equal amounts of chalcopyrite. In part it is contemporaneous with the chalcopyrite in period of formation, but probably continued to form somewhat longer. Both sulphides are later than magnetite, hematite or pyrite. In these deposits pyrite is an unimportant mineral and the early deposition of iron usually takes the form of magnetite and specularite. The similarity of contact metamorphic deposits to the group previously described suggests that the initial conditions under which deposition took place in the former were not far removed from the early phases of deposition of the ore-minerals in magmatic-pneumatolytic deposits. The occurrence

of iron oxides rather than pyrite is probably susceptible of the same explanation as mentioned on page 319 . The similarity in this feature to the ores of magmatic origin suggests that the original conditions of metallic deposition in the contact-metamorphic ores were of an intensity comparable to those in the initial stages of deposition under magmatic and pneumatolytic conditions. It is possible that the temperatures in the early stages are above those at which sulphur can remain united with iron as pyrite. Where pyrite is abundant, as in the Bisbee ores, magnetite is usually of little importance. The possible importance of sulphur as a mineralizer associated with the copper is again emphasized.

The ore minerals are all later than the high-temperature silicates of the garnet zone. In the three deposits studied, the ores show a distinct tendency to occur between intensely altered rock on one side, and unaltered rock on the other, a fact which supports Umpleby's generalization[1] that in contact-metamorphic deposits the ore usually occurs on the limestone side of garnet zones. Under the microscope, the sulphides may be seen to be later than garnet, diopside, vesuvianite, and epidote, but more closely associated or contemporaneous with chlorite and sericite, and followed by carbonates and in one case (Marble Bay, Texada Island) by zeolites.

From these relations, it is evident that the bornite does not occur under the intense early phases of the mineral-

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1. loc. cit.

ization, but is a product of conditions of increasingly hydrothermal tendencies along with chlorite and sericite, finally dying out as the conditions become favorable for the formation of carbonates and zeolites.

At Bisbee, where bornite is an important ore-mineral, although in general less abundant than chalcopyrite, the same general relations hold, except in different degrees. The high temperature silicates again are earlier than the ore-minerals, but they are developed only in a narrow contact zone. According to the work of Bonillas, Tenney and Feuchère,[1] the chalcopyrite and bornite are later than the sericite, and are most commonly accompanied by widespread silicification. This relation and the occurrence of the sulphides in almost unaltered limestone suggest that in deposits of this type the formation of bornite takes place under similar or milder conditions than in the deposits of the direct contact-metamorphic type.

Bornite in Deposits of Hydrothermal Origin

It has been apparent in the discussion of deposits under other headings that a portion of the bornite in nearly all cases is associated with minerals of hydrothermal origin, and should be assigned to that genetic class. Consequently, there remain for discussion here, only the deposits of simple

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1. loc. cit.

[illegible]

[illegible]

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hydrothermal character, which lack those interesting features such as pneumatolytic products or dependence on igneous contacts which would bring them under discussion elsewhere. The veins of sulphides in unaltered limestone at Kennecott are believed to be of hydrothermal origin, but on account of the many puzzling features presented, they have been treated under a separate heading.

The deposits of this group in which bornite is an important mineral are chiefly vein deposits. The ores are usually accompanied by the development of sericite, chlorite and to a less extent epidote and carbonates in the wall rock, and quartz in the veins themselves or in the immediate walls.

Pyrite and magnetite (as at the Superior Mine, Engels) are invariably earlier than the copper minerals. The pyrite, which is abundant at Magma and at Butte, is apparently brecciated and recemented by chalcopyrite, bornite, and the later minerals, but it is probable that the actual fracturing which made channel-ways for the later phases of the mineralization was very slight, and that the brecciated appearance is largely due to the character of the replacement and structural properties of the pyrite. In the Magma deposit, which offers a simple and fairly typical example of a normal hydrothermal deposit, the pyrite is accompanied by silicification and sericitization of the wall-rock. The development of quartz continued, however, with the deposition of chalcopyrite and bornite. The formation of chlorite in

the county-rock probably accompanied this phase of the mineralization. Carbonates as usual are later products.

The complex relations at Butte have not been considered in detail in connection with this work, for they are being studied intensively at present as a separate problem by another investigator. In general, however, it may be said that the primary mineral associations of the gangue, alteration products and ore-minerals indicate that bornite is formed under conditions of intermediate intensity, similar in a broad way to the simpler relations at Magma and elsewhere.

In the ore-deposit at the slightly developed Superior Mine near Engels, California, the mineralization associated with the bornite indicates an unusually wide range in conditions of formation for this type of deposit. The earliest minerals in the wall rock and the veins are albite, tremolite and biotite, all indicating fairly high temperatures. The early deposition of iron takes the form of magnetite. The copper follows with sulphur, in part late and in part associated with epidote, chlorite, and sericite. The opening stages of the mineral deposition at Superior are close to the border line between pneumatolytic and hydrothermal conditions. The continuation of the processes of mineralization under mild conditions is indicated by the occurrence of heulandite in notable amounts. Ordinarily in bornite deposits of hydrothermal origin, the various min-

erals are more closely related in conditions of formation, although the mineralization may have been longer continued and greater in extent.

The bornite-chalcopyrite deposits in basic lavas afford a special class of hydrothermal deposits different in origin and different in many details from the preceding deposits. The deposits in the Nikolai greenstone in the Kennecott district are the only ones of this type which have been studied in connection with this investigation, but the constancy of features which this type of ore-deposit shows gives the treatment presented on previous pages a general value. The evidence indicates that the ores were concentrated from the basic lavas themselves, in part perhaps by means of emanations closely following their extrusion, but in some cases very probably by the circulation of heated waters through the flows under later conditions. The veins are rarely large or persistent, but the mineralization is widely distributed. The characteristic gangue is quartz, carbonates and epidote, with widespread development of chlorite in the wall-rock. Albite, datolite and zeolites are also formed in association with the sulphides, but are usually not abundant. Bornite is later than the quartz, epidote and chlorite, but in part earlier than the carbonate. It is later than pyrite, and although closely associated with chalcopyrite, it lags somewhat behind as usual.

Bornite in Replacement Ores in Unaltered Limestone

The only deposits of this type which have been considered are the ores in the Chitistone limestone at Kennecott. The primary features of these ores have been discussed in great detail, and will not be reconsidered here. The primary ores are believed to have been formed by ascending heated solutions which had derived their copper content from the underlying greenstone formation. The chief problem in connection with the Kennecott ores is the primary or secondary nature of the chalcocite. The critical features depend upon the interpretation of the alteration of bornite, and will be discussed under that heading.

Bornite Deposited from Cold Meteoric Solutions

Ores of the "Red Beds" Type. Bornite occurs in small amounts in ores of the "Red Beds" type in various parts of the world.[1] Chalcocite is the usual sulphide in deposits of this sort, but in many districts it is associated with small amounts of hematite, pyrite, bornite, chalcopyrite, and covellite, accompanied by malachite, azurite, limonite and other products of oxidation. The ore-minerals are commonly replacements in the sedimentary rocks, usually at-

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1. For bibliographies of deposits of this type and discussion, see Lindgren's Mineral Deposits, pp. 369-376; for European localities, Stelzner and Bergeat, Die Erzlagerstätten, 1904, pp. 388-439.

Duplication of Books in Technical Libraries

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1. For bibliographies of [illegible] see [illegible] Electronic Engineering, [illegible] [illegible] Electronic Industries, [illegible] [illegible] Electronic Industries, pp. [illegible].

tacking the cementing material or entombed carbonaceous matter. Where sulphides other than chalcocite occur, the ore-minerals are usually in sequence, the earlier being partially replaced by the later.

Excellent microphotographs of wood structure replaced by hematite, pyrite, bornite and chalcocite have been published by A. F. Rogers.[1] In material from Sierra Oscura, New Mexico, it is clearly shown that the bornite was derived in part at least by the replacement of pyrite, and the chalcocite by replacement of the bornite. A little chalcopyrite and covellite are also found as replacements of bornite. The replacement of hematite by pyrite, the two ages of hematite, and the climatic changes deduced by Rogers, are, however, difficult to follow.

The question of the origin of ores of the "Red Beds" type cannot be regarded as finally settled,[2] but most writers are in agreement that in general the sulphides were deposited from cold meteoric solutions.

Bornite nodules in the lower beds of the Chitistone limestone near Kennecott,[3] and in shales in Mashonaland, southern Rhodesia, described by F. P. Mennell,[4] are most

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1. Origin of Copper Ores of the "Red Beds" type, Econ. Geol., Vol. II, pp. 366-380, (1916).
2. The Sierra Oscura ores and others of the "Red Beds" type have been attributed to heated ascending solutions by L. C. Graton, Prof. Paper, No. 68, U.S.G.S., (1910).
3. p. 261.
4. Mineralogical Magazine, Vol. 17, p. 111, (1914).

probably to be attributed to meteoric agencies.

Secondary Bornite. Contrary to general belief, bornite is very rarely of secondary origin in sulphide deposits. As has been emphasized previously in many places, bornite is frequently a replacement of earlier ore-minerals, such as magnetite, pyrite, enargite, or, to a slight extent, chalcopyrite, but the field relations make it very apparent in all cases studied, that the sequence of minerals was due to primary causes and in no way related to the processes of secondary enrichment. The deposition of bornite ores in general shows no variations with the factors which control the development of secondary sulphides, and it is safe to conclude that the distribution of rich bornite ores will not be limited to the range of surface agencies.

Bornite of secondary origin, however, has been observed in microscopic quantities in many deposits. At Globe, small veinlets of bornite cutting chalcopyrite areas seem clearly associated with the development of chalcocite and are probably of similar origin. In the Bisbee ores fine veinlets of chalcocite in bornite have been observed to continue as veinlets of bornite when a chalcopyrite area was intersected.

The "halos" of bornite round chalcopyrite grains in a field of chalcocite are most readily interpreted to be an intermediate step in the alteration of chalcopyrite to chalcocite. In ores from the Magma Mine this structure is

well illustrated. Secondary bornite of this sort has also been observed under the microscope in many of the porphyry ores, as those of Brigham, Ray, Morenci, and Ely. In all these cases, however, the quantity of the secondary bornite is almost negligible, when compared with the total sulphide.

Pyrite grains in chalcocite, where the enriching changes are well advanced and probably intense, are frequently observed to be surrounded by thin rims of chalcopyrite which are in turn bordered by a similar rim of bornite forming composite "halos". In general this relationship is to be interpreted as a result of the alteration of pyrite by enriching solutions, and the chalcopyrite and bornite are merely intermediate steps in the transformation of pyrite to chalcocite. An attack on pyrite by the enriching solutions under conditions unfavorable for the removal of iron would probably be the best suited to yield the intermediate products. Halos of this sort have been observed in secondary ores from a number of the camps just mentioned and give very certain evidence of the partial replacements of pyrite.

At Butte, bornite-chalcopyrite halos have been observed in ores from almost all depths explored. For the most part they are identical with the relations noted in secondary ores, but chalcopyrite halos have been observed about pyrite grains set in a wide field of bornite[1] which

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1. D. A. Hall, Private communication, Febr. 1917.

cannot with certainty be ascribed to secondary agencies.

Summary of Conditions under Which Bornite Has Been Formed

Bornite forms an important ore in only one well known deposit of the direct magmatic type (Ookiep). In this case, the bornite is the last of the series of rock and ore-minerals, and was probably deposited under late magmatic conditions. The initial segregation of the copper is attributed to direct magmatic differentiation, but the final adjustments and concentration of the sulphides into ore-shoots is believed to have been caused largely by the action of mineralizers. The temperature under which the bornite was formed, is much lower than that at which the rock minerals usually separate, and probably is comparable to the temperatures prevailing during the crystallization of pegmatites.

In several deposits, bornite forms a primary constituent of pegmatites, or differentiated dikes of somewhat similar origin, but here again it is one of the latest minerals to have been deposited, and was probably formed at temperatures lower than that commonly assigned for the crystallization of pegmatitic quartz, in the neighborhood of 575°C. The bornite in pegmatites is rarely abundant enough to give promise of becoming of commercial value.

Rich bornite ores occur in several well known contact-metamorphic deposits. Again the mineral is clearly later than all high temperature products; it replaces earlier

contact-metamorphic silicates such as garnet, diopside, vesuvianite, and is the latest important sulphide of primary sequence.

From the study of ores of the contact-metamorphic type, and also of ores in veins of hydrothermal origin, there is strong evidence that bornite in greatest quantities is formed under hydrothermal conditions, usually a little later than the period characterized by the formation of pyrite and epidote, and about contemporaneous with the most intense development of sericite and chlorite. The formation of bornite ceases, or continues in a diminishing, feeble way, under later conditions which are characterized by the development of carbonates or zeolites.

The penetration of bornite grains by sericite or chlorite laths has been interpreted by A. F. Rogers as a proof that the sulphides are replaced by these silicates. The relation has been observed in ores from many districts in the course of this work. In nearly all cases, the evidence is capable of two interpretations, viz. that of Rogers and the commoner view that the silicates are inclusions in the sulphides. Veinlets of sericite or chlorite have not been observed cutting bornite or chalcopyrite areas.[1] At Engels there is evidence that the chlorite was produced to-

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1. It should be noted that the ore-minerals cut by veinlets of chlorite shown in Tolman and Rogers' photographs of Engels' ores (loc. cit. fig. 77), are magnetite and hematite and not sulphides. This is not mentioned in the text. (p.63.)

ward the close of the bornite forming period, but the intimate relations with the sulphides and the distinct examples of corrosion of chlorite by bornite are difficult to explain under Rogers' interpretation. Except for the absence of notable corrosion, the relations of the sericite to bornite are the same as those of the chlorite. Summarizing the relations observed in the districts studied in the course of this work, the conclusion that the development of sericite and chlorite usually preceded or was contemporaneous with the formation of bornite harmonizes the evidence most satisfactorily.

Bornite with associated chalcopyrite in veins in basic lavas affords another example of the hydrothermal origin of the mineral. This type of deposit, however, is rarely of commercial importance. The Kennecott deposits in limestone also constitute an example of bornite ores formed under relatively mild conditions of pressure and temperature although probably from heated solutions.

Small quantities of bornite in ores of the "Red Beds" districts, and occasional nodules in impure limestones or shales indicate that the mineral may be capable of formation from meteoric waters.

The occurrence of secondary bornite as a replacement of primary sulphides by the processes of surface enrichment, gives positive evidence that bornite can be produced in cold solutions. The amount of secondary bornite, how-

ever, is very small. It is rarely observed except under the microscope.

It is apparent from the preceding summary that bornite forms under an usually great variety of conditions. The deposits in which it occurs range in origin from late magmatic to feeble hydrothermal, and also include those formed by cold meteoric agencies.

In deposits commonly classed as magmatic, bornite is uncommon; it is of wider distribution in deposits of the pneumatolytic type, although rarely in large bodies; it is

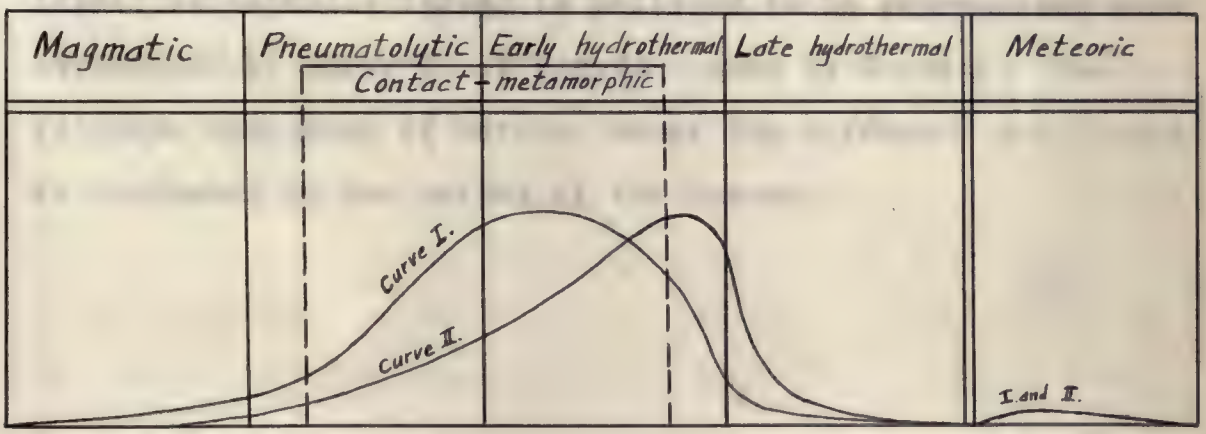

Fig. 39. Diagram of Distribution of Bornite.

Curve I. Distribution of bornite based on classification of containing deposit.

Curve II. Distribution of bornite based on conditions of formation of bornite itself.

of widest distribution and greatest commercial importance in veins and other replacements classed as hydrothermal deposits; it is only in very small and unimportant amounts in deposits from cold meteoric solutions, including secondary sulphide ores. Curve I of Fig. 39 illustrates this distribution of bornite in a qualitative way in the different classes of deposits. As has been mentioned, however, the bornite in most of the deposits is later than the group of minerals -- among which gangue minerals are given greatest weight -- upon which the classification is based. Consequently the summary of conditions under which the bornite itself is actually formed is believed to be represented more accurately by Curve II of Fig. 39 than by Curve I. The relative abundance of bornite under the different conditions is indicated by the height of the curves.

THE ALTERATION OF BORNITE

Introduction

In most of the ore-bodies described on previous pages, the formation of the primary sulphides ceased with the close of the period of bornite deposition. Here and there, a little chalcopyrite, galena, tennantite, or tetrahedrite may have continued to form in a feeble way, as a line of fine blebs or an indefinite veinlet, but for the most part, the only sulphides which occur in abundance later than the bornite, are those included in the group of which chalcocite is the most prominent member. In the majority of cases, the chalcocite and the related minerals may be easily recognized as products of the superficial alteration of the ore-body, but in some deposits, where they persist to great depths, or where certain peculiar relationships to the other sulphides exist, it may be difficult to determine whether they are the result of secondary processes or are the final members of the series of primary minerals.

Field Relations.

The field relations afford conclusive evidence of the secondary origin of the chalcocite in many cases, especially where the enrichment is confined to a limited zone beneath

Introduction

the oxidized ores, and is succeeded below by leaner sulphides which show little change with increasing depth. These relations are usually more strongly marked in deposits where pyrite-chalcopyrite ores constitute the primary sulphides, than where bornite is an important constituent. With the same depth of ore exposed to oxidation, it is evident that less copper is made available for the enriching solutions in the case of the pyritic ores than when bornite ores are oxidized. This and the greater addition of copper necessary to convert pyrite and chalcopyrite to chalcocite than to accomplish the same change in a bornite ore, tend to limit the enrichment to a narrower and more definite zone in the case of the pyritic deposits.

The results of a calculation in a simple, idealized case emphasize this point. Assume for a basis of comparison two ores, one containing 10% bornite by volume, and the other 10% chalcopyrite, both in an inert gangue. The bornite ore would assay 11.1 per cent copper, the chalcopyrite ore 5.20 per cent. Assume that the deposits are in a vertical position, and that oxidation penetrating to a depth of 100 feet, had completely converted the copper into the soluble sulphate, which descended into the sulphides beneath, and had reacted with them according to the equation

$$5\ Cu_5FeS_4 + 11\ CuSO_4 + 8\ H_2O = 18\ Cu_2S + 5\ FeSO_4 + 8\ H_2SO_4$$

in the case of the bornite, and according to the equation:--

$$5\ CuFeS_2 + 11\ Cu\ SO_4 + 8\ H_2O = 8\ Cu_2S + 5\ FeSO_4 + 8\ H_2SO_4$$

in the case of the chalcopyrite.[1] If the replacement of the primary sulphides by chalcocite was complete as far as the influence of the cupric sulphate extended, the bornite would be converted to chalcocite for a depth of 226 feet below the bottom of oxidation, and the chalcopyrite to a depth of 45.2 feet. The volume changes involved on the basis of these equations are almost negligible. The ore would be increased from 11.1% copper to 15.6% copper in the case of the bornite deposit, and from 5.2% copper to 15.6% copper in the case of the chalcopyrite deposit, but in the bornite deposit the enrichment would extend five times as deep as in the other.

Under natural conditions, only part of the original copper in the oxidized zone would be available for the enriching processes. Varying amounts would remain fixed as carbonates, silicates and oxides. Losses of copper are inevitable in the movement of the sulphate solutions. While these factors would reduce the thickness of the chalcocite zone and the depth of enrichment, they would tend to be balanced by the fact that at many places the enrichment would be only partial, and therefore that some chalcocite would be formed deeper than indicated in the ideal case.

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1. E. G. Zeis, E. T. Allen, and H. E. Merwin, Secondary copper sulphide enrichment, Econ. Geol., Vol. II, pp. 407-503, (1918).

$$\left(\frac{\partial \rho_{12}}{\partial t}\right)_{\text{coll}} = -\frac{\pi}{\hbar}\left(\Omega_{12}^2 + \Omega_{21}^2\right)\delta(\omega_{12}-\omega)$$

$$\left(\frac{\partial \rho_{21}}{\partial t}\right)_{\text{coll}} = -\frac{\pi}{\hbar}\left(\Omega_{12}^2 + \Omega_{21}^2\right)\delta(\omega_{12}-\omega)$$

in the case of the resonance.[1] If the polarization of the primary excitation be initially random, in the sense of the incidence of the beam of metastable atoms, the intensity of the fluorescence is expected in analogy (in a manner of speaking) with the case of scattering, to be a multiple of $(3/2)^2$ that given. The values computed assuming an RF H field of 10 gauss equations are plotted graphically. The rms width is increased from $(1/\tau)$ to $(2/\tau)$ because in $\Delta\omega$ equals 2π the case of the intensity, but 2π full widths at $(1/\tau)$ apart, not 2π full widths at $(1/\tau)$ apart in the case of the simultaneous decay, but in the Doppler imposed the experiments really exist time to check on all the predictions.

Small effects, particularly shifts of the resonance in the maximum slope should be available for the experiment sensitive transmission. Doppler shifting would create first an asymmetry, although not serious. Finally of course the attention to the existence of the multiple excitation. Only three factors would create the difficulty of the existence of the quantum case the light is emitted, this would tend to be broadened by the fact that as many photons the radiation energy be very small, and therefore that some resonance would be created beyond in the first case.

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1. E. C. Yeh, E. J. Zimmerman and G. E. Harris, Technical Report (Unpublished), Rice U., Feb. 17, p. 6, (1967).

Although the actual depths indicated in the computation are of little value, the ratio of the depth of enrichment in a bornite ore to the depth of enrichment of a chalcopyrite ore is probably a close expression of the conditions which actually obtain in nature. The contrast in depth of enrichment between lean pyritic ores and bornite ores is even more striking than in the case calculated in which a rich chalcopyrite ore was assumed, for in such lean deposits not only is there less copper made available by a given depth of oxidation and leaching, but also a given quantity of copper will produce a much smaller quantity of chalcocite. In the case of the pyritic deposits, the change in value from the secondary ore to the primary ore is much greater than in the bornite deposits, but the development of the secondary sulphides is far more extensive in the latter under similar conditions.

From the preceding considerations it is apparent that while the field relations usually give definite information concerning the secondary or primary nature of chalcocite ores in pyritic deposits, based on their behavior with depth,[1] the evidence in the case of deposits in which bornite is an important primary constituent, may be more difficult to interpret. If the enrichment in bornite ores is confined to a shallow zone, the secondary origin of the chalcocite is even more definitely established than in the

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1. See A. Locke and E. H. Perry, Interpretation of Assay Curves for Drill Holes, Trans. A.I.M.E., Vol. 54, pp. 93-99, 1916.

case of similar relations in pyritic ores, but in none of the bornite ores which have been studied, does the continuance of the chalcocite with depth alone establish the primary nature of the replacement. The possibility cannot be denied that the enrichment of bornite by surface agencies may take place under favorable circumstances as deep as any of the chalcocite-bornite ores observed in the course of the work of the Secondary Enrichment Investigation.

Selective Enrichment.

The relative ease with which the change from bornite to chalcocite takes place is an important factor in explaining the features of enriched bornite ores. The commonest ore-minerals associated with bornite may be placed in the following sequence with respect to their resistance to alteration to chalcocite: pyrite, enargite, sphalerite, chalcopyrite, bornite. Between the pyrite and enargite may be grouped tennantite and tetrahedrite, and between the chalcopyrite and bornite, galena should be placed, but the evidence fixing the positions of these members of the series is not entirely satisfactory, and their exact places are not definitely established. The information by which the relative ease of replacement by chalcocite is established is gained in small part from field observations, but chiefly from the relations observed under the reflecting microscope which alone are really reliable.

Evidence such as that afforded by the disseminated ores in Sacramento Hill at Bisbee for example clearly shows the greater resistance of pyrite to alteration than of bornite. There, it will be recalled, the ratio of pyrite to chalcocite in the enriched portions of the deposit is approximately the same as the ratio of pyrite to bornite in the deeper ores, which indicates clearly that the pyrite was little changed by conditions which had completely altered the bornite. Under the microscope, the comparisons are based on the volumes of the different primary minerals which have been replaced by chalcocite or its associated products under the same conditions, or on the persistence of grains of one mineral which remain in fields in which others have been partially or completely replaced. Examples are numerous of veins of chalcocite or covellite in bornite pinching or disappearing when the crack along which they have developed passes into chalcopyrite. (Figure 155.) Enargite frequently remains unenriched in material in which the chalcopyrite has been attacked.

Pyrite itself is attacked to a certain extent, but the amount of chalcocite which is now attributed to pyrite replacement, is much less than it was a few years ago when the relations and distribution of the primary minerals were less thoroughly understood. The later minerals, chalcopyrite and bornite particularly, are often in replacement relationships to the pyrite, either breaking it in veins or, where

more abundantly developed, occurring as a cementing material about the grains. (Figures 93,94). Where the bornite or chalcopyrite are completely replaced by chalcocite, the same forms are inherited, and in the resulting product the chalcocite appears to have been derived by the replacement of pyrite, although as a matter of fact this mineral may have remained completely resistant to the chalcocite attack.

There is little evidence of exact comparative value with respect to tennantite and tetrahedrite. Under some conditions, they are corroded by the chalcocite, but usually they remain resistant in fields in which surrounding sulphides are partially or completely altered.

The evidence with respect to sphalerite and galena is somewhat conflicting. According to Lindgren[1], the alteration of sphalerite to covellite is the deepest change which takes place at Morenci, but this statement was made before the reflecting microscope was in common use among geologists and has not been confirmed by the evidence it has yielded concerning these ores. R. M. Overbeck[2] states that sphalerite is more easily replaced by chalcocite than is bornite but his photographic evidence is not convincing. For the most

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1. The copper deposits of the Clifton-Morenci District, Prof. Paper, 43, U.S.G.S., (1905).

2. A metallographic study of the copper ores of Maryland, Econ. Geol., Vol. II, pp. 151-178, (1916). See figure 9.

part sphalerite is slightly more resistant to the secondary sulphides than chalcopyrite. Galena is not very commonly seen in relations which throw definite light on its ease of replacement, but on the whole it is fairly certain that it is more resistant than bornite. There is apparently no tendency for blebs of galena in partially enriched bornite to be sought out by the chalcocite, while on the other hand chalcocite has been observed associated with blebs of bornite in areas of galena. In the Marble Bay deposit at Texada Island, there is evidence that galena is attacked by chalcocite more readily than chalcopyrite, and it is probable that this relation is the general one. Intermediate reactions between those described for pure galena and those described for steinmannite[1](the arsenic-antimony variety) have been observed. It is reasonable to assume that the rate of reaction with copper sulphate solutions would also vary, which might account for its present indefinite position in the sequence.

From the results of experiments in the Geophysical Laboratory[2], it was found that the sequence of minerals, based on the weight of material altered in two months in 1.25 per cent solution of cupric sulphate at 40°C, is as as follows; galena (greatest) (5.5), bornite (2.5), sphaler-

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1. J. Murdoch, Loc. cit., Mineral tables, p. 133.

2. E. G. Ziess, E. T. Allen, and H. E. Merwin, Loc. cit.

ite (1.1),chalcopyrite (1.). Based on volume, the series is :-- galena (3.0), bornite (2.1), sphalerite (1.1), chalcopyrite (1.0). In precipitating power, bornite follows chalcopyrite, but in volume of mineral altered it follows galena. As the microscopical determination of the ease of replacement is based on volume relations, the second series is more significant for comparison with natural relations. The ease of replacement of bornite is well shown, but the strong reaction in the case of galena is surprising. However, as is mentioned by the authors of the paper, the amount of material dissolved varies notably with the surface exposed, and it is very probable that in minerals which possess a good cleavage the actual surface available for attack is greatly increased by incipient cracks along the cleavage directions, developed during the grinding. This factor would be especially important in both galena and sphalerite, and may explain their higher position in the series established by chemical work than observations of associations of these minerals in ore-deposits would accord them.

Microscopic Relations.

Knowledge of the microscopic relations between the earlier minerals and the group of later sulphides is always necessary to interpret the nature of changes in any ore-deposit, but it is of especial value in the case of bornite

ores, where the greater depth to which enrichment can extend makes the relations observed in the field less definite as criteria, and throws a higher relative value on the interpretation of intimate structures observed under the microscope.

Simple Structures. Under conditions of enrichment of normal intensity, bornite, as do the other sulphides, alters to chalcocite along veinlets whose course is clearly determined by preexisting cracks, or along grain or gangue boundaries, where definite channel ways are afforded for the enriching solutions. (see figures 41, and 74). The distribution of the chalcocite is dependent largely on these easily recognized causes, and usually shows little tendency to be controlled by the more delicate influences of crystallographic nature or other internal properties of the bornite.

In certain deposits in ores near the bottom of the enriched zone, the chalcocite works its way around the edges of the individual bornite grains within the massive material which results in a peculiar pattern on the polished surface of large and small bornite areas apparently floating in chalcocite. Where the bornite grains are small, replacement advances more rapidly, consequently a matrix of finer grains is often eaten out from around the larger, producing a pattern on the polished surface to which C. F. Tolman, Jr[1].

1. Loc. cit., Fig. 13.

has given the descriptive name, "ice-cake structure".

The Lattice Structure. The replacement of bornite, however, under certain conditions may develop other structures more complicated than the simple veinlets or rims described above. In one prominent type, which is commonly termed the "lattice structure", the replacement advances in a differential manner, apparently controlled by crystallographic factors. Plates of chalcocite, covellite or chalcopyrite develop in the bornite, parallel to two or three structural directions, and when sectioned by the polished surface yield a reticulate grill of intersecting strips or bands in a field of bornite. (Figures 43, 74, 77, 134, 137, 146, and 152). Chalcocite is the most abundant mineral in this relation with bornite, but covellite and chalcopyrite are by no means uncommon. The structures are very similar in the three cases, and indicate with little doubt that the orientation of the plates is due to the common host mineral. Enargite and luzonite (?) have also been observed in lattices in bornite, but they are uncommon and appear to be of primary origin.

On the polished surface, the lines of the replacing mineral in the lattice structure are usually oriented parallel to three directions but a fourth direction is shown occasionally, which suggests that the bornite yields to the attacking solutions along octahedral planes. The octahedral cleavage cracks, developed by pressure on the polished surface, form a pattern very similar to the lattice structure,

an agreement which strongly suggests that this peculiar replacement structure was determined by the bornite cleavage. The octahedral form of both the lattice structure and the pressure cleavage in bornite is farther suggested by their similarity to the etch-structure of synthetic isometric chalcocite which is known to follow the octahedral parting.[1] (Figures 139 and 140.)

The replacement origin of the minerals associated with the bornite in the lattice structures is convincingly shown in most of the deposits studied, but since other explanations have been advanced by two writers for similar material in the Butte ores, it will be necessary to consider the evidence in detail.

Chalcopyrite, when developed in bornite in association with chalcocite or covellite of recognized secondary origin, nearly always assumes the lattice form (figures 48, 78, 134), and its distribution near veinlets or in the neighborhood of the secondary sulphides clearly indicates its dependence on the same agencies as those which produced the copper sulphides. There can be little doubt that the mineral is a common product of the alteration of bornite. Chalcopyrite plates in bornite similar to those of the lattice structure have been produced artificially in the Geophysical Laboratory[2] by treating bornite with cupric sulphate

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1. E. Posnjak, E. T. Allen and H. E. Merwin, Loc. cit., p. 524

2. E. G. Zies, E. T. Allen, and H. E. Merwin, Loc. cit., p. 479.

solutions. Chalcocite is the chief product of the reaction but within the bornite grains away from the direct attack by the reagents, chalcopyrite was formed. As chalcopyrite is also produced by the action of sulphuric acid on bornite[1], its formation in this experiment and in nature is attributed by the members of the Geophysical Laboratory staff to the action of sulphuric acid produced by the alteration of bornite to chalcocite or covellite.[2] In cases where the development of chalcopyrite is accompanied by shrinkage, it is quite probable that the alteration was accomplished partly or wholly in this way (figures 43 and 45), but where no volume change can be observed, which is the commoner case, there must have been a distinct addition of iron to the space originally occupied by the bornite. The reaction is probably more complicated than simple acid attack.

From the evidence in the ores themselves and from the synthetic work in the Geophysical Laboratory it may be regarded as definitely established that chalcopyrite associated with bornite in the lattice structures is of replacement origin, and that it is closely associated with the alteration of bornite to chalcocite and covellite, a change which ordinarily takes place under secondary conditions.

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1. Ibid., p. 476

2. Ibid., p. 480

The possibility of "reticulate intergrowths" of bornite and chalcopyrite under primary conditions, however, cannot be entirely eliminated for somewhat similar structures were formed artificially at the Geophysical Laboratory in a sulphide melt from which products close in composition to bornite and chalcopyrite respectively crystallized. But, while there is a general resemblance in a broad way between the structures, the details are distinctly different, and easily distinquished. Forms exactly similar to these synthetic structures have never been observed in natural products. All the available evidence, however, indicates that the chalcocite, covellite and chalcopyrite in lattice structures with bornite is of replacement origin.

The common distribution of covellite spines around the margins of grains or along the border of veinlets in bornite, often closely associated with chalcocite or products of oxidation, makes the replacement and the secondary origin of covellite in this relation so apparent that other interpretations have not been suggested.

The chalcocite in the lattice relation with bornite is believed to be of replacement origin by Graton and Murdoch[1] who first described the structure. In a later paper by J. C. Ray[2], dealing with the Butte ores, the opinion is

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1. Loc. cit.

2. The paragenesis of the ore minerals in the Butte district, Montana, Econ. Geol., Vol. 9, p. 479, (1914).

[illegible]

expressed that the bornite in lattice structures in the "covellite zone" was formed by the elimination of iron from the chalcocite along crystallographic planes. He states that the precipitation of chalcocite in a colloidal state is strongly suggested and that the formation of chalcopyrite and bornite is believed to be due to a reaction of iron locally taken into solution. In a discussion[1] published more recently, however, he apparently regards the chalcocite in the lattice patterns to be an incomplete replacement of bornite, and his excellent photographs strongly support this view. Julius Segall[2] from a study of similar material, interprets the relations to indicate a replacement of chalcocite by bornite, along crystallographic directions of the former mineral. W. L. Whitehead[3], however, from a study of material from many localities, supports the earlier interpretation, advanced by Graton and Murdoch, and regards the evidence presented by Ray and Segall to be unconvincing.

In all the ores studies in the course of this work, there has been distinct evidence that the chalcocite in the lattice structures is closely associated with chalcocite, which from its occurrence in veins or rims, is plainly of replacement origin. The beginnings of the lattice patterns

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1. J. C. Ray, Econ. Geol., Vol 11, pp. 179-185, (1916).

2. The origin and occurrence of certain crystallographic intergrowths, Econ. Geol., Vol. 10, p. 467, (1915).

3. The paragenesis of certain sulphide intergrowths, Econ. Geol., Vol.11, p. 10, (1916).

have often been observed as fine lines penetrating the bornite from the edges of ordinary veinlets or rims. In these early stages, the stripe of chalcocite are most readily interpreted as veinlets in the bornite. All degrees of chalcocite abundance may be explained as the results of the widening and extension of these veinlets, with the accompanying gradual reduction and elimination of the isolated rhombs and triangles of bornite. When examined under high magnification, these residual shapes are often found to have blurred bluish borders, due to a fringe of tiny bornite specks severed but not yet destroyed by the advance of the chalcocite. The blue color in these transition zones may be due in part to exceedingly minute bits of covellite, which is known to form as an intermediate product. Hazy boundaries of this sort are common accompaniments of replacement by secondary chalcocite, and these relations in the lattice structure prove beyond doubt that the chalcocite is of metasomatic origin.

While the views advanced by Ray and Segall may seem to explain the relations observed in certain special cases, it is believed that the abundant evidence of replacement exhibited in many districts offers a more generally applicable interpretation. None of the relations described by Ray in his earlier paper presents any objection to the replacement origin of the chalcocite. Segall's arguments are based largely on the resemblance of the lattice patterns to the triangular etch-structure of chalcocite, and on the

occurrence of bornite in vein-like bands along cracks in chalcocite or bornite-chalcocite areas. Chalcocite with the triangular type of etching, however, is uncommon except where associated with bornite. The usual orthorhombic etch-pattern of chalcocite is not similar to the bornite-chalcocite lattice structure. Moreover, it is difficult to conceive of the mechanics of a replacement process which would develop angular grains of the new mineral between regular vein-like strips of other. The interpretation would demand two ages of bornite, for the evidence of the later age of some of the chalcocite is undeniable in most deposits.

Borders of bornite, such as Segall illustrates, along irregular cracks in areas of chalcocite or of chalcocite and bornite (figures 146 and 150), often in the lattice relationships, certainly resemble veinlets of bornite cutting the surrounding material. As a matter of fact, in this kind of occurrence as well as in related structures in which marginal rims of bornite surround fields of mixed chalcocite and bornite, detailed examination under high magnification often shows that the bornite is not later than its surroundings, but is instead residual and is yielding, though with apparent resistance, to the same kind of replacement by chalcocite as that which may be shown by the bornite in the general field of replacement.[1]

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1. For an excellent example see J. Murdoch, Op. cit., Frontispiece, Fig. 2.

Irregular strips of bornite in fields partially altered to chalcocite, or rims of bornite about areas containing chalcocite and bornite have been observed, which on first inspection apparently support Segall's interpretation, viz., that the bornite is a replacement of the chalcocite. However, detailed examination under greater magnification rarely fails to reveal fine veinlets of chalcocite or other relations indicating partial alteration of the bornite to the chalcocite, which make it highly probable that the elongated forms of the bornite are inclusions and not veins. The possible explanation may be suggested that this peculiar preservation of the bornite from chalcocite attack was due to the concentration of outgoing iron solutions produced by the replacement reactions.

The differential attack of the chalcocite in the lattice structure whereby certain strips are altered and others left suggests the explanation that the alteration was produced slowly under mild conditions, probably by dilute solutions acting for long periods of time. Where enrichment is intense, the lattice structure is rare; it is commoner in the deeper parts of the enrichment zone where bornite is the only mineral altered, or in protected, impermeable cores. This distribution is clearly shown at Bisbee. The structure is well known in chalcocite ores of accepted secondary origin, and it seems probable that the milder and more slowly acting processes of secondary enrichment would be more favorable for its production

than the more intense action of heated ascending solutions of the period of primary mineralization. The occurrence of a structure of such delicacy under two sets of contrasted conditions, while possible, would be rather unusual, and the presence of the lattice or closely related structures in the ores at Kennecott and at Butte may be regarded as an argument in favor of a secondary origin for the chalcocite in these disputed occurrences.

Residual Structures Related to the Lattice Structure. Associated with the lattice structure are various modifications, in part closely related in form, and in part transitions to other structures. Of the former, the most prominent is the occurrence of definite, sharply bounded plates of bornite in the chalcocite, or chalcocite-bornite lattice, which apparently remain resistant, to the replacing reactions. (Figures 143, 147 and 148). From the appearance of these plates on the polished surface, the name "spine structure" has been commonly applied to it, but as this expression is not accurately descriptive for the rather blunt sections of the bornite plates, as revealed on a polished surface, the term spline structure[1] is suggested. Where associated with the chalcocite-bornite lattice, the plates or splines are usually oriented symmetrically but not parallel to the lattice directions. The edges against the chalcocite commonly yield evidence of replacement, and

1. Spline, a thin plate in a slot, a term used in connection with machinery and carpentry.

where the enrichment is intense, they may be broken by numerous irregular cross veinlets of chalcocite. (Figure 143.) They rarely yield a lattice pattern by their decomposition, but the alteration along their edges is often controlled by the directions of the adjoining lattice. (Figures 147 and 149.) The strips of bornite isolated between long bands of chalcocite in the lattice structure are rarely as long as the splines described above, and are usually broken by regular cross-bands of chalcocite. Their contacts with the chalcocite are of the hazy indefinite type for the most part. Consequently there is little indication that splines are normal residues of this sort. There is a distinct suggestion that the bornite in these forms is of different character from that which filled the surrounding areas, for the difference in resistance to chalcocite replacement is very marked and is difficult to explain on other grounds. This possibility will be discussed more fully on later pages.

Numerous, sharply defined grains of bornite are often left scattered through the chalcocite field, after the replacement has almost obliterated the angular bornite residues of the lattice structure. The grains are usually very small, mere dots on the polished surface, but by their true color they are in notable contrast to the indefinite residues of bluish bornite which mark the last stages of the lattice replacement. The specks are usually irregularly scattered but their distribution preserves the lattice pattern by their

avoidance of the white stripe of chalcocite which mark the lines along which the first replacement was accomplished. In some of the Butte ores in which this spot structure is particularly prominent, (Figure145), the arrangement of the grains sometimes shows curving banded patterns imposed upon a field in which the lattice structure is still strongly evidence.

The spot structures are most prominently developed in the Butte and Bisbee bornite-chalcocite ores. In some cases, where the grains were somewhat larger than usual, they assume smoothly irregular forms, very similar to blebs of bornite in the graphic structure.[1] While the most typical graphic structures have not been observed in this association, where the surrounding chalcocite had clearly been formed by lattice replacement of bornite, the approach to true graphic forms is so close in many cases, as to afford a strong argument that the graphic and lattice structures are of related origins. As in the case of the splines, the existence of a more resistant type of bornite is suggested by the presence of these sharply defined grains, remaining in fields in which all the rest of the bornite has been nearly or completely altered.

Chalcocite Derived from Bornite.

Chalcocite, which has been derived from bornite

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1. See photograph by J. C. Ray; Econ. Geol., Vol. 11, p. 184, Fig. 6, 1916.

through the stages of a lattice replacement, retains a structure parallel to the lines of the lattice, which is revealed by bands and strips of white in a blue field on the polished surface, or by the triangular etch-pattern when treated with reagents. (Figures 119, 107, 108, and 142.) The lines of white chalcocite, when possible to trace them into bornite-chalcocite lattice areas, are the lines of the initial strips which penetrate the bornite fields. The disintegration of the angular bornite residues between the lines yields a bluish type of chalcocite. The hazy bluish tints about the bornite margins are largely due to minutely spaced, almost submicroscopic specks of bornite, isolated by the advancing chalcocite, but in some cases the color is probable due to fine shreds of covellite, formed with the chalcocite. The blue color of the chalcocite suggests the presence of dissolved cupric sulphide.[1]

Etched with dilute nitric acid or potassium cyanide solution, chalcocite of this blue and white type usually develops a perfect etch-structure, with three or four sets of equally developed cracks, identical in orientation with the lines of the lattice structures. Where the etch-patterns may be traced into a bornite-chalcocite lattice, the etch-cracks are invariably found to be parallel to the bands of chalcocite. With one possible exception no cases have been

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1. Eugen Posnjak, E. T. Allen, H. E. Merwin, Loc. cit.

observed in which this structure occurs in chalcocite that is known to be a replacement of any sulphide other than bornite.

The orthorhombic form of chalcocite, which is stable below 91° C, possesses an etch structure on the polished surface which may be easily distinguished from the isometric type or from that inherited from the lattice structure. Orthorhombic chalcocite possesses a strong etch-cleavage parallel to the base, a weaker one parallel to the side pinacoid, and an imperfect one parallel to the front pinacoid.[1] On the polished surface, etching usually yields one set of strong parallel cracks with or without a second series of weaker cracks at right angles. Chalcocite formed under secondary conditions would possess the orthorhombic form, for the temperatures of such processes are always well below 91° C.

However, in a number of deposits chalcocite of known secondary origin yields the triangular etch-pattern closely similar to that of high temperature chalcocite, but in all cases thus far encountered the chalcocite has been found to be a replacement of bornite, from which its structure was probably inherited, presumably through the lattice stage. The explanation has been definitely confirmed in certain ores.

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1. Joseph Murdoch, Op. cit., p. 107.

1. Hawkes Expedition, op. cit., p. 107.

An inheritance of crystallographic orientation of one mineral by another is not an uncommon phenomenon, but the inheritance of internal crystal structure is undoubtedly rare. It is perhaps difficult to comprehend the inheritance of that particular molecular arrangement which determines cleavage, but it is conceivable that certain planes of weakness, parallel to the cleavage directions, which directed the advance of the first strips of lattice chalcocite, could be preserved as apparent cleavages or pseudo-partings in the chalcocite in the same way that a visible crack which has localized replacement on a coarser scale, often remains as a line of weakness within the final product. This property, which is neither cleavage nor parting merits a separate designation, and for it the term herifrage (from the Latin heres, heir as in inheritance, and fragilis, from frango, break) is proposed by L. C. Graton and the writer. It may be defined as the property of breaking or etching along particular planes of systematic arrangement acquired by replacement of an earlier mineral which possessed cleavage in corresponding directions.

The triangular etch-structure is known in secondary ores although it is not a very common feature, but it cannot be limited to chalcocite of secondary origin. It is most strikingly developed in the great chalcocite ore-bodies at Kennecott, for which a primary origin is favored. There is the possibility that the development of bornite lattice struc-

ture and of the related triangular pattern in chalcocite is facilitated at temperatures above 91° C, at which the chalcocite possesses an isometric form similar to that of bornite, but the relationship is certainly not confined to such conditions. Although the distinction between the isometric structure of high temperature chalcocite and the structure inherited from bornite cannot always be made, it is certain that material possessing this structure is either of primary nature or, if secondary, is a replacement of bornite. Consequently, chalcocite of this sort would either be expected to continue with depth, or to be succeeded by primary bornite, which would not mean a very serious decrease in copper values.

THE GRAPHIC STRUCTURE

Description

The term "graphic structure" has been applied to the relation between bornite and various other sulphides in which the minerals are associated in a manner resembling myrmerkitic or micropegmatitic intergrowths of quartz and feldspar. The structure is characterized by the association of the two minerals (rarely more) in minutely sinuous strips of varying widths or elongated blebs and lobes of sub-equal size. The strips are simple or irregularly branched and in some cases complexly interdigitated. A rough parallelism in one or more directions is not uncommon, and in some instances it approaches a regularity sufficient to suggest a relation to crystallographic directions. The contacts between the two minerals are nearly always sharp, and rarely offer any evidence indicating relative sequence. As many tongues of bornite extend into the associated mineral, and as many projections of the latter are apparently severed by the bornite as the reverse. In other words the boundaries of the two minerals are mutual.

These associations have commonly been called "graphic intergrowths", but since the word "intergrowth" is often used in the sense of simultaneous formation of the two components, and since such an origin cannot be universally established, a term that is merely descriptive, like

graphic structure is to be preferred, for it implies no theory of origin.

The following minerals have been observed associated with bornite in the graphic structure:-- chalcopyrite, galena, enargite, tetrahedrite, tennantite, klaprotholite, and chalcocite. Of these, the bornite-chalcocite association is far more abundant and of much greater interest than the others, but as it will be treated at greater length, the occurrence and significance of the less common minerals will be discussed first.

Primary Minerals Associated with Bornite in the Graphic Structure.

The ordinary primary structure exhibited between bornite and chalcopyrite is not similar to the graphic form (Figures 47 and 67), but in a few cases, as at the Evergreen Mine the relations between the two minerals are practically those ordinarily observed in the well-known bornite-chalcocite graphic pattern. (Figures 45 and 46.) The bornite and chalcopyrite are generally believed to be essentially contemporaneous, and in this particular case there is every reason to believe that the graphic structure, which is exhibited between them, is of direct primary origin, and the result of the simultaneous deposition of the two minerals. In the neighborhood of the graphic structures, however, the rather common feature of slight primary corrosion of chalcopyrite by bornite can usually be seen, which is regarded as an indi-

cation that the initial conditions of contemporaneous deposition were succeeded by those under which chalcopyrite yielded a little to bornite replacement.

Bornite and galena in graphic relations are more common. The distribution of the two minerals indicates that both are primary in all examples in which the structure has been observed, and the absence of all evidence of replacement nature, indicates that the two minerals are of simultaneous deposition and that the structure between these minerals likewise is that of a contemporaneous intergrowth. The bornite usually predominates over galena and is the host mineral. The bornite-galena intergrowths differ from the usual form of the graphic structure by the marked variation in size of the galena blebs (figures 89 and 90), which range in some cases from fairly coarse grains down to the finest specks that can be distinguished under the oil-immersion lens. An intergrowth of bornite and galena, coarse enough to be visible with the unaided eye, has been described by H. F. Collins.[1]

Tennantite and tetrahedrite are uncommon in the graphic structure, but occur occasionally accompanying other minerals in this relation. In certain fields of graphic structures between chalcocite and bornite a few of the light colored blebs are found to be tetrahedrite or tennantite, but in the same shapes and relations as the more abundant chalco-

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1. Mineralogical Magazine, Vol. 13, p. 336, (1903).

cite. A similar association of tetrahedrite and tennantite with galena-bornite graphic intergrowths has been noted. Graphic blebs of enargite in bornite have been seen in a few specimens from Butte. An unknown pinkish mineral from Butte also shows graphic relations to the bornite. A few grains of klaprotholite, a rare sulphobismuthite of copper, which has been doubtfully identified in bornite from the Marble Bay Mine, Texada Island in connection with this work occurs in forms closely simulating the blebs of the graphic structure. A. F. Rogers,[1] however, has described klaprothotite in graphic relation with bornite in ores from Butte and other camps, but in general the mineral occurs in very unimportant quantities. Rogers states that it is later than the bornite.

Chalcocite in the Graphic Structure.

The minerals in the graphic relation which have been described in the last few paragraphs are of primary origin, and with the possible exception of klaprotholite, are probable intergrown simultaneously with the bornite. The origin of chalcocite in the graphic structure with bornite is less easily settled, however, and offers a problem of definite commercial as well as scientific interest. The relations upon first inspection suggest a contemporaneous

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1. Econ. Geol., Vol. 17, p. 584 (see Fig. 4), 1916.

origin for the chalcocite and bornite, and hence that the chalcocite was formed under primary conditions. The abundant distribution of chalcocite as a secondary mineral in most camps, however, makes any relation which may indicate a primary origin worth especially careful study, and demands a critical examination of the evidence before any other interpretation than secondary can be accepted.

Bornite and chalcocite are occasionally associated in a structure identical with that often observed between chalcopyrite and bornite. (Figures 101 and 102.) The structure is similar to the graphic pattern in that the two minerals exhibit mutual relations for the most part, but differs in the larger size of the blebs and in their often pointed and scalloped forms. The two structures are probably of about the same origin.

Literature. The graphic structure between bornite and chalcocite was first described by F. B. Laney[1] in ores from the Virgilina District, Virginia. It had been previously suggested[2] that the deep chalcocite ores in the district were of primary nature, and this view was supported by Dr. Laney who regarded the graphic structure as the result of a primary intergrowth of chalcocite with bornite. Graton

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1. F. B. Laney, Proc. of U. S. Nat. Museum, Vol. 40, p. 580; and The relation of bornite and chalcocite in the copper ores of the Virgilina District of N. C. and Va., Econ. Geol., Vol. 6, pp. 399-411, (1911).
2. L. C. Graton, Mineral Resources, U.S.G.S., 1907, Part I, p. 620.

and Murdoch[1] in their paper on the sulphides of copper accepted the graphic relation as an indication of contemporaneity, and hence a criterion for the primary nature of the chalcocite. The same interpretation was given the structure by C. C. Gilbert and G. E. Pogue[2] in ores from the North Mt. Lyell Mine in Tasmania. R. M. Overbeck[3] described chalcocite and bornite in graphic structure in ores from Maryland, and believed that the two minerals are contemporaneous. It is suggested in the description of a microphotograph that the bornite may in part be later than the chalcocite.

Bornite and chalcocite in irregular associations somewhat akin to graphic relations were described by A. F. Rogers[4] in 1914, and believed by him to be of replacement character. The similarity to the structures described by Laney was pointed out, and it was suggested that the same origin may be applied to both. No proofs were advanced. In an earlier article on the Butte ores,[5] the same writer came to the conclusion that the deep chalcocite at Butte

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1. L. C. Graton and Joseph Murdoch, loc. cit., p. 768.
2. C. C. Gilbert and G. E. Pogue, The Mt. Lyell Copper district of Tasmania, Proc. U. S. Nat. Museum, Vol. 45, pp. 609-625.
3. R. M. Overbeck, A metallographic study of the copper ores of Maryland, Econ. Geol., Vol. 11, pp. 151-178, (1916); see also, B. S. Butler and H. D. McCaskey, Copper ores of the New London Mine, T.A.I.M.E., Vol. 49, p. 287, (1915).
4. A. F. Rogers, Secondary enrichment of copper ores with special reference to microscopic study, Mining and Scientific Press, Oct. 31, 1914, p. 686.
5. Upward Secondary Enrichment and chalcocite formation at Butte, Montana, Vol. 8, pp. 781-794, (1913).

is in part a replacement of bornite, but specific reference was not made to the graphic structure. Chalcocite in graphic structures in bornite from Engels, California was described by A. F. Rogers,[1] and believed to be due to a peculiar break-down of bornite into chalcocite. He expressed the doubt whether graphic relations due to simultaneous intergrowth ever exist between these minerals. In similar material, Ray,[2] as has been mentioned, apparently regarded both the bornite and chalcocite as replacements of covellite, but considered them to be of simultaneous origin. Later[3] he stated that the graphic structure may originate by the replacement of bornite by chalcocite. The view has been advanced by L. C. Graton[4] for graphic structures in general that some may be simultaneous intergrowths and others may originate by replacement.

The replacement origin of the chalcocite in the graphic structures is favored by W. L. Whitehead,[5] whose views are well supported by his discussion and excellent microphotographs. A. F. Rogers,[6] in a later article, comes

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1. A. F. Rogers, Engels article, Econ. Geol., Vol. 9, p. 381. (1914).
2. J. C. Ray, Econ. Geol., Vol. 9, pp. 463-487, (1914).
3. Econ. Geol., Vol. 11, pp. 179-185, (1916).
4. L. C. Graton, Trans.A.I.M.E., Vol. 52, p. 597, (discussion).
5. W. L. Whitehead, The Parageneesis of Certain Sulphide Intergrowths, Econ. Geol., Vol. 11, pp. 1-13, 1916.
6. A. F. Rogers, The so-called graphic intergrowth of bornite and chalcocite, Vol. 11, pp. 587-593, Econ. Geol., (1916.)

to very similar conclusions and advances some additional arguments.

It is apparent from this brief survey of the literature, that there is notable divergence of opinion concerning the origin of the chalcocite in the bornite-chalcocite graphic structures. The evidence in most cases admits of more than one interpretation, and it is difficult to advance arguments of sufficiently compelling nature to settle the question in a satisfactory and final manner. Our own observations confirm the relations described by the other workers in nearly all cases, but our interpretation of their value as arguments differs somewhat. The evidence favoring the two opposing views of origin will be summarized in order in the following paragraphs, and on the later pages, the significance of the various relations will be discussed.

Summary of Evidence. Evidence favoring a contemporaneous origin for the bornite and chalcocite in the graphic structure may be summarized as follows:

(1) the similarity of the graphic structure to the structures of metallic eutectics,

(2) to the structure of quartz and orthoclase in micropegmatite; and

(3) to the structures between bornite and primary ore-minerals;

(4) the sharp contacts and mutual boundaries between the bornite and chalcocite;

(5) the occurrence of the chalcocite in the heart of bornite grains with no visible channel ways for the entrance of altering solutions;

(6) the lack of relation between the chalcocite and grain boundaries and gangue contacts;

(7) the contrast to the structures of bornite and chalcocite in specimens in which the chalcocite is definitely known to be of secondary origin;

(8) the parallel orientation of chalcocite in the blebs over considerable areas.

The arguments supporting the view that the chalcocite is a partial replacement of the bornite may be enumerated as follows:

(1) the occurrence of occasional microscopic veinlets of chalcocite connecting the chalcocite lobes;

(2) the lack of discernible boundaries between the chalcocite of the veinlets and the chalcocite of the lobes;

(3) the common crystallographic orientation of the chalcocite in each;

(4) the gradation and merging of chalcocite of replacement origin with the chalcocite of the bornite-chalcocite graphic structure;

(5) the presence of small spines of chalcopyrite in the bornite blebs;

(6) the replacement by chalcocite of blebs of other minerals (as klaprotholite or galena) associated in graphic relations with the bornite; and

(7) the presence of bornite "residues" arranged with a faint suggestion of the lattice structure in chalcocite blebs of the graphic structure.

The points in both lists will be discussed in the order of their enumeration, beginning with those which favor contemporaneous origin of the two minerals.

(6) the [illegible] [illegible]
[illegible]

(7) the [illegible] [illegible]
[illegible]

[illegible]

[illegible]

[illegible]

(1) the [illegible]
[illegible]

(2) the [illegible]
[illegible]

(3) the [illegible]
[illegible]

(4) the [illegible]
[illegible]

(5) the [illegible]
[illegible]

(6) the [illegible]
[illegible]

(7) the [illegible]
[illegible]

[illegible]

Arguments Favoring a Contemporaneous Origin.

(1) and (2). Although the similarity between the graphic structure and metallic eutectics is striking, the evidence is not sufficient either from our knowledge of conditions of ore-deposition or from experimental work to state that the graphic structure in sulphides is of eutectic or eutectoid origin. Whitehead[1] draws attention to the discordance between the structure of metallic eutectics and the graphic structure, shown by the presence of an excess of only one constituent in the former, while in the latter, both constituents, bornite and chalcocite, are commonly present in addition to the association of the two in the graphic areas. Relations strictly in accord with artificial products formed in a closed system and in a limited time, however, should not be expected under the changing conditions which must have obtained during the formation of the natural sulphides. Both quartz and feldspar in excess are common accompaniments of micropegmatite yet this structure is believed by nearly all observers to be a simultaneous intergrowth of the two minerals. E. S. Bastin[2] has presented evidence which indicates that the coarser graphic structures in pegmatites are not of eutectic nature, but he believes that the components are of contemporaneous origin. The sulphides may likewise

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1. Loc. cit. p. 5.

2. E. S. Bastin, Origin of the pegmatites of Maine, Jour. Geol, Vol. 18, 1910. pp. 297-320. Bull. No. 445, U.S.G.S., 1911.

[illegible]

[illegible]

[illegible]

be simultaneous intergrowths even though not eutectics, although the argument based on similarity of pattern is slighily weakened if it cannot be admitted that an origin similar to the metallic eutectics is possible. Further relations of the graphic structure to eutectics are discussed on later pages.

(3) The graphic relations between chalcocite and bornite are very similar to the associations between bornite and certain primary minerals which have been described on preceding pages. For the most part, the minerals of this group are unknown or uncommon as replacements of bornite, and in general there is good evidence to believe that they are of contemporaneous origin with the bornite.

(4) While sharp contacts are common features of sulphides in primary relations to each other, their existence in the graphic structures does not constitute definite evidence of contemporaneous origin. Examples are numerous of chalcocite, clearly of secondary origin, with sharply defined boundaries against bornite, and indications are accumulating that many primary associations of minerals with clean-cut outlines may likewise be a result of replacement.

(5) The occurrence of chalcocite in the graphic patterns in the heart of bornite grains has now been observed in enough cases to greatly reduce the possibility that chalcocite is related to definite visible channel ways which are unexposed by the section revealed on the polished surface. It is con-

ceivable and probable that material can be transferred by channel-ways of sub-microscopic size, or by diffusion through the massive sulphide, for movement of this sort must take place in the ordinary process of replacement to supply new material and to remove waste products through the compact layer deposited in the earlier stages of the reaction. The replacement of chalcopyrite or bornite by chalcocite due to descending copper solutions affords a definite example of this action for although the replacing sulphide adheres firmly to the primary mineral, and forms an apparently impermeable coating, the alteration often goes on to completion in spite of it.

Even assuming this mechanism, no explanation is offered for the frequent lack of alteration of the bornite in the outer portions of the grains, which are normally most easily affected by the replacement processes. Under the usual conditions, there is no known reason why the attacking solutions should have withheld action until the centers of the grains were reached. While graphic chalcocite is by no means confined to the heart of grains in general, the occurrence of many definite cases in this relation and the difficulty of explaining the association by the ordinary mechanics of replacement, offers a strong argument against the view that the structure could originate by the metasomatic alteration of a homogeneous mass of bornite.

(6) and (7) The increasing number of observations of chalco-

cite and bornite in graphic relation from deposits of various types, indicates that the association of the two minerals in this form possesses many properties which are as constant and as characteristic as those common to sulphides of recognized replacement origin. The distribution of chalcocite developed by metasomatic processes, generally shows a marked control by the crystalline structure of the material replaced or by definite and obvious channelways, such as grain surfaces or mineral contacts especially those with gangue, or cracks penetrating the material attacked. It is equally characteristic of chalcocite in the graphic structures to be independent of these features. Distribution suggesting crystallographic control is sometimes seen (Figure), but in general no guiding influences can be detected which would direct the advance of the replacing mineral into the forms characteristic of the graphic pattern. The indifference of the chalcocite to the channelways offered by gangue boundaries is a very common feature of the graphic structure. It is well shown in figures 86, 87, and 88, in ores from the Superior Mine near Engels, California. In both examples the line of attack which normal replacement reactions would be expected to follow would be the contacts of the magnetite crystals with the bornite. There is no marked preference shown by the chalcocite for this position. In the neighboring Engels Mine, where there is a notable amount of secondary sulphides, the contacts of the gangue minerals and espe-

cially the chlorite laths embedded in the bornite were found to be particularly sought by the replacing chalcocite. In the similar ores at the Superior deposit, however, chlorite laths were observed included in bornite-chalcocite graphic areas with apparently no influence on the distribution of the chalcocite. (Figure 86). It should be mentioned, however, in this particular case, that the quality of the argument depends on the age assigned to the chlorite. The arguments have been advanced on earlier pages (110-113) why we concluded that the chlorite is earlier than the bornite. According to the interpretation given by A. F. Rogers, however, the cross-cutting relations in this and other cases, would be considered the result of the replacement of bornite and primary chalcocite by chlorite. The general proposition, however, that chalcocite in the graphic structures shows little dependence on gangue boundaries is based on numerous observations in many deposits, and does not rest for final proof on the association with chlorite or sericite alone. From the relations discussed under this and the earlier headings, it is fairly certain that the chalcocite in the graphic structure was not formed by replacing solutions attacking all bornite with equal vigor along lines usually selected for such alteration. The independence of gangue boundaries and other ordinary channelways which is exhibited by many graphic

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1. Econ. Geol., Vol. 9., pp. 359-391, (1914).
Econ. Geol., Vol. 11, pp. 121-126, (1916). See Fig. 3.

structures is a strong argument against the replacement hypothesis unless some other control can be shown to exist, as would be afforded by a variation in bornite character of such nature and so distributed that it would guide the alteration away from its usual loci and into the peculiar forms of the graphic pattern.

(8) The parallel orientation of the chalcocite in the various blebs and lobes of the graphic structures is clearly brought out by the etch-pattern. This character of the graphic chalcocite was first described by Laney,[1] who regarded it as proof that the chalcocite was a skeletal crystal formed with the bornite in a manner very similar to the quartz in a quartz-feldspar graphic intergrowth. This explanation is attractive and meets with few objections, but its force is greatly weakened by another possibility. It is known that chalcocite may inherit its crystallographic orientation from the bornite which it has replaced. Consequently, if of replacement origin, the common crystallographic orientation of the various blebs is easily explained as an inheritance from bornite. The etch-structure of the bornite in the blebs of the graphic structure usually shows that the bornite is also in parallel orientation throughout, and sometimes for a little distance into the surrounding field. The strong direction of the etch-pattern of the bornite, however, is

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1. Loc. cit.

not necessarily parallel to the strong direction of the chalcocite cleavage.

With these modifications it is apparent that the parallel orientation of the chalcocite in the graphic structures possesses little value as an argument favoring contemporaneous origin for the two minerals.

This exhausts the arguments which have been advanced in favor of the contemporaneous origin of the chalcocite and bornite, and on a whole it is apparent that they present a strong case against the view that the graphic structures could originate by the replacement of massive, homogeneous bornite. They make it clear that many properties of the graphic structure are closely related to those of contemporaneous intergrowths, but nevertheless the evidence does not show with certainty that the chalcocite in the graphic patterns is of contemporaneous origin with the bornite. Additional considerations are presented on later pages.

Discussion of Arguments Favoring a Replacement Origin.

The arguments of the second group, viz., those favoring a replacement origin for the chalcocite, are discussed in order below.

(1) Whitehead[1] states that the graphic structure originates by the replacement of bornite by chalcocite along minute interlacing veinlets. The characteristic pattern is attributed

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1. Loc. cit., pp. 6-9, Figures 6, 7 and 8.

[illegible] [illegible]
[illegible]

[illegible]

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to a stage of the metasomatism in which these veinlets are broadened in places and the bornite masses rounded where the veinlets intersect. In many graphic areas, however, even the fine veinlets described by Whitehead cannot be observed under the oil-immersion lens, and from our experience, it would seem that although they are not an uncommon accompaniment of the graphic structure, they are not invariably present. If the graphic structure originated in the manner suggested by Whitehead, it is difficult to understand why the degree of replacement in these structures, now known from many widely separated districts, should be so similar. Intersecting lace-works of veinlets have been observed in bornite in which no tendency toward the graphic structure could be detected, but between this stage and the typical graphic structure, no relations have been noted which could be intermediate steps in the change. No explanation is offered by this plan of origin for the differential character of the replacement. Chalcocite developed in this way would not be expected to differ so distinctly in distribution from replacement chalcocite in general, consequently the objections raised by the points discussed under preceding headings remain in force. Replacement under these conditions would be expected, as is stated, to yield rounded bornite blebs or lobes, but not rounded chalcocite masses. The mutual relations between the two minerals offer serious objections to this theory of origin.

(2) Etching shows that chalcocite of veinlets breaking bornite blebs does not continue across intervening chalcocite fields. In some cases,[1] where a crack was observed to continue, it seems very probable that the chalcocite along such channels is later than the chalcocite of the graphic areas, yet there is usually no definite boundary between the two chalcocites at the main chalcocite-bornite margin. The veinlets are usually very narrow, consequently the line of contact between the two chalcocites on the polished surface would be very short, and a break in continuity might not be visible. A physical boundary, emphasized perhaps by a variation in color, might be expected, if the chalcocite were of two ages, but its absence does not afford a convincing argument in favor of the hypothesis that the chalcocite in the graphic structure is of the same age as that in the veinlets.

(3) The directions of the etch-pattern of the chalcocite in the small veinlets are difficult to determine, and from our own work, there is no evidence to indicate that the two chalcocites are in parallel crystallographic orientation. From Whitehead's statement, however, that the chalcocite of the veinlets is continuous with that of the blebs it is to be inferred that he believed tha chalcocite of the veinlets to be in crystallographic orientation with that of the blebs. But,

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1. Superior Mine, Engels, California for example. p. 138.

even if this is established, it is not a conclusive argument against the later age of the veinlets for the orientation of the chalcocite in them could conceivably be determined by that of the pre-existing chalcocite, just as the orientation of the later quartz in a quartzite is determined by that of the quartz in the original sand-grains.

(4) In addition to the fine veinlets discussed above, it is very common to find chalcocite of the graphic structures passing without detectable break into chalcocite which is clearly of replacement origin. (Figures 70, 75, and 82.)[1] Bands of chalcocite forming alteration rims about bornite areas, widen into patches of chalcocite interwoven with bornite in the graphic pattern. Furthermore, fine veins or tongues of chalcocite in some cases penetrate the sharp walls of the graphic bornite blebs or the surrounding massive bornite. (Figure. 82,) Blue hazy boundaries, of the kind already described, are sometimes found between bornite and chalcocite in the graphic association, and show beyond question that the replacement conditions had been active to some extent at least, though in parts of the same graphic areas, however, these hazy boundaries may be entirely wanting.

These various relations can of course be explained as the effect of later secondary chalcocite imposed on earli-

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1. A photograph by A. F. Rogers in Econ. Geol., Vol. 11, (1916), p. 588, Fig. 6, illustrates this point well.

er material deposited contemporaneously with the bornite. It is possible that later chalcocite would so weld itself to the earlier that the boundary would show no break in color, crystallographic orientation or other properties, but it is more difficult to accept this explanation in these cases than in those previously discussed where only fine veinlets are concerned. Except for the graphic relation itself, there is often no reason to assign to the chalcocite of these structures a different origin from that of adjoining material which without question has been formed by replacement of bornite.

On the whole, the relations between the graphic chalcocite and material of replacement origin are in many cases so intimate and so general, that they constitute a very serious argument against the universal application of the hypothesis of strictly contemporaneous deposition for the two minerals in the graphic structure. The strength of this objection, however, is very greatly reduced by a modification of the hypothesis which will be presented later.

(3) The formation of chalcopyrite as a product of the alteration of bornite to chalcocite has been commonly observed in material from many districts, as has been mentioned previously, and consequently the occurrence of chalcopyrite spines in the bornite of the graphic areas suggests a replacement origin for the associated chalcocite. The argument is weakened, however, by the fact that chalcopyrite is not a common accompaniment of the graphic structure, and that there is the

possibility that it may be the product of neighboring replacement reactions, unassociated with the chalcocite of the graphic areas, for the formation of secondary chalcopyrite at any point commonly precedes the formation of chalcocite, and may take place some distance ahead of the first traces of enrichment. On account of these reasons the occurrence of occasional spines of chalcopyrite in the graphic structures does not offer positive support for the hypothesis of replacement origin for the graphic structure.

(6) It is conceivable and easily granted that chalcocite associated with bornite in the graphic structure could have originated by the replacement of an earlier mineral similarly associated with the bornite. The other minerals which have been observed in this association with the bornite, however, are in general less susceptible to replacement by chalcocite than is the bornite itself and as a matter of fact, with the exceptions noted below, no evidence whatever to support such a view has been observed. Galena may be an exception but there are certain peculiar features commonly exhibited by the galena-bornite graphic structures which are not found in the chalcocite patterns, and which make it probable that the chalcocite was not derived from this mineral. A. F. Rogers[1] has described specimens from several districts in which klaprotholite and chalcocite are associated in the same

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1. Econ. Geol., Vol. 11, pp. 582-593, (1916).

graphic area with bornite, and he believes that the chalcocite was formed by the replacement of the klaprotholite blebs, which in turn had previously replaced bornite. While this interpretation is a possible one, and may be sufficient in certain special cases, the rareness of the mineral and the absence of partial stages of its replacement, makes it extremely unlikely that it offers an explanation which is generally applicable. It should be noted that even if this hypothesis is accepted, the explanation is only postponed one step, for it is still difficult to understand how klaprotholite replaces bornite in these peculiar forms.

(7) In material from Engels and from Bisbee, fine strips of bornite were observed in chalcocite between bornite blebs similar to those of the graphic structure. The arrangement and association of the bornite strips suggests that they are residues from a replacement of the lattice type. If this is the case, the replacement terminated against the lobes of graphic bornite with a sharp even boundary as if against a mineral of great resistance to alteration. Lattice structures sharply limited to certain areas have been described on earlier pages. Usually the evidence suggests that under certain conditions, chalcocite in the lattice pattern can develop uniformly in all parts of certain grains without extending in the slightest to neighboring grains, but only in the few cases in the two districts mentioned have relations been observed which definitely suggest that the grains

subject to this peculiar type of metasomatism may be of graphic outline. The spots and specks of apparently more resistant bornite which remain scattered through the field in certain Butte and Bisbee ores, after the main mass of the bornite has been swept away by lattice replacement, sometimes occur in twisted, curved blebs suggesting graphic forms. Since they are clearly residues in chalcocite of replacement origin, their resemblance brings support for the view that the chalcocite in graphic areas originated in this way. If this were the case, however, it would seem that partial stages should be commonly found, and the practical lack of these is a strong objection to this genetic mechanism.

From a review of the arguments on both sides of the controversy, it is apparent that neither view can be established without serious modification. The hypothesis of contemporaneous origin fails to explain important relations in many examples, and the hypothesis of simple replacement origin is also inadequate to give a complete solution. The evidence is so conflicting that neither extreme view can be established to the exclusion of the other, and it indicates the difficulty of explaining all features associated with the graphic structures by a single kind of mechanism.

Hypothesis of Contemporaneous Deposition Modified by Replacement. The most serious objection to the hypothesis of strictly contemporaneous origin is the close association often observed between chalcocite in the graphic areas and

chalcocite of replacement origin. A modified form of the hypothesis, however, reconciles the evidence if it is assumed that although the chalcocite was initially deposited contemporaneously with the bornite, it continued to form after the bornite had become unstable, which resulted in the development of replacement relations. The hypothesis thus modified is more in agreement with the usual relations observed between primary minerals than is the view of strictly contemporaneous deposition. The relations between the bornite and chalcocite would be very similar to those believed to exist between chalcopyrite and bornite in many deposits. The sequence of the minerals implied by this hypothesis is expressed graphically in Fig. 40 .

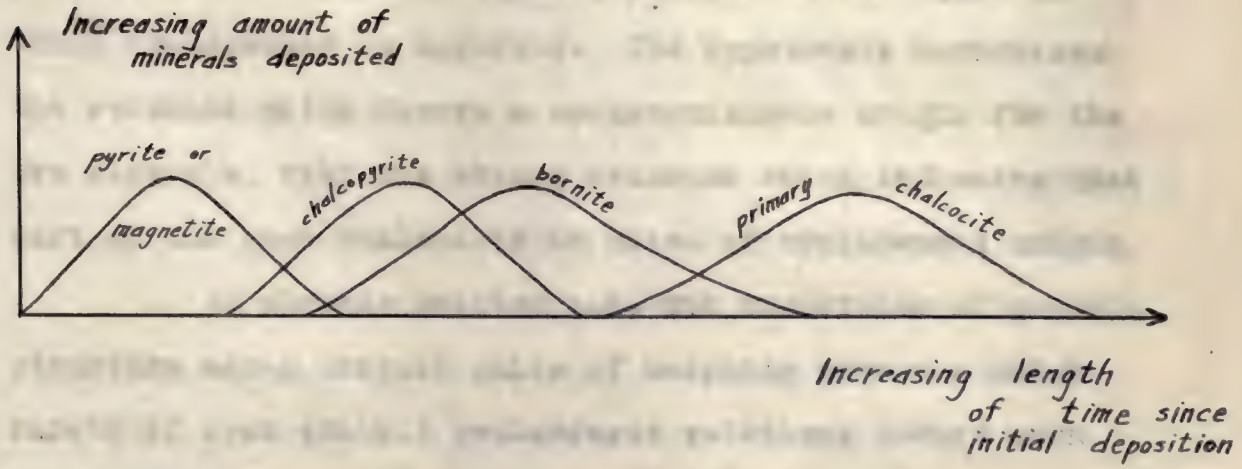

Fig. 40. Diagram of Sequence of Bornite and Chalcocite According to the Primary Theory for the Chalcocite in Graphic Structures.

The hypothesis in this form assumes that with the changing conditions of the period of primary mineralization, a point was reached at which chalcocite commenced to deposit with the bornite, but with progressive changes in concentration of the solutions (probably a gradual reduction in the iron-copper ratio), bornite ceased to form, became unstable, and tended to alter to chalcocite. It is conceivable that the contemporaneous deposition of the two minerals was of temporary eutectic character, of which the graphic form is the expression, but that these conditions were generally interrupted more or less promptly by the addition of components favoring the production of chalcocite, which thus brought about the super-imposition of replacement phenomena upon the eutectic pattern. By this hypothesis, graphic structures which are unassociated with any evidence of replacement are explained equally as well as the types in which replacement is apparent. The hypothesis harmonizes the evidence which favors a contemporaneous origin for the two minerals, with the strong evidence which indicates that part of the same chalcocite is often of replacement origin.

As already pointed out, the occurrence of graphic structure among certain pairs of sulphide minerals which rarely if ever exhibit replacement relations toward each other makes it reasonable to conclude that they are contemporaneous intergrowths, especially as we know that simultaneous graphic structures can be produced as final crystallizations

in alloys. Among these natural intergrowths the mineral common to most of them is bornite, from which, because of its sequence position, the inference may be drawn that graphic structures are most favored in the late stages of mineralization. This deduction may render more acceptable the idea that the graphic structures between bornite and chalcocite are actual intergrowths, since primary chalcocite if it exists at all, is in part later and probably just later than bornite. No certain weight, however, can be attached to this speculation.

If the interpretation is correct, it of course means that part of the chalcocite in replacement relations with bornite may be of primary origin, a fact which makes chalcocite the last member of the sequence of primary minerals. The sequence, in its simplest terms, would be magnetite or pyrite — chalcopyrite — bornite — chalcocite. The first three members whose positions are definitely established, are in agreement with the sequence if arranged according to decreasing iron and increasing copper; hence on chemical grounds chalcocite is the logical end member.

Although chalcocite is definitely known to be of secondary origin in most of the important copper deposits, and hence formed at ordinary temperatures, synthetic results indicate that it is stable at higher temperatures, and may be formed under the usual conditions which are believed to have prevailed during the deposition of primary sul-

phides. In the Geophysical Laboratory, chalcocite crystals have been formed in the dry way at a temperature above 350°C, and in the wet way at temperatures as high as 250°C.[1] Increase of temperature is also known to accelerate the rates of the reactions by which secondary chalcocite is formed.[2]

In general chalcocite in the graphic patterns occurs most prominently in the deeper parts of bornite-bearing deposits.[3] Nearer the surface the structure is usually obliterated by the more complete replacement of the bornite by chalcocite, and evidence of its former existence is largely removed. For the most part, the field relations indicate that the chalcocite in the graphic structures at any definite place in the ore was formed earlier than the period of intense development of secondary chalcocite.

The evidence of primary origin offered by the deep chalcocite, while very suggestive, cannot be regarded as final, however, for the reason that in none of the cases now known are the workings deep enough to be beyond the influence of descending solutions, and beyond the point at which secondary chalcocite has developed from bornite, with a few exceptions mentioned later ~~but~~ whose character is not fully determined, ~~the secondary alteration of bornite even at~~

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1. Eugen Posnjak, E. T. Allen, and H. E. Merwin, loc. cit., pp. 530-521.
2. E. G. Zeis, E. T. Allen, and H. E. Merwin, loc. cit.
3. Butte, Engels, Virgilina, for examples.

~~great depths attained there cannot be eliminated.~~ In the Virgilina District,[1] the mines are not over 450 ft. deep, and although there is very definite evidence that the rocks are extremely tight, the long continued exposure to erosion makes it surprising that the bornite ores are not more completely enriched.

If the hypothesis of primary chalcocite is accepted, it becomes necessary to attempt to distinguish between primary chalcocite of replacement origin and secondary chalcocite in the same relations. At the Superior Mine near Engels, and in the Kuskulana District, Alaska, the secondary chalcocite formed under recent physiographic and climatic conditions is so feeble that it is in definite contrast to the chalcocite in the earlier graphic or related structures. But in most cases where the secondary sulphides are well developed under present conditions, chalcocite definitely recognized as secondary in origin, may be traced without change into chalcocite of replacement origin intimately associated with the graphic areas. No break in structure or other properties can be detected, and any limit to the extent of the secondary chalcocite is quite arbitrary.

While this is obviously a difficulty in the way of the acceptance of the hypothesis, the possibility of chalcocite assuming similar replacement forms and similar physical properties under primary conditions as under

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1. F. B. Laney, loc. cit. p. 364.

secondary cannot be denied. Although chalcocite formed at temperatures above 91°C. is isometric, it alters to the usual orthorhombic form when cooled, unless it contains over 8% dissolved cupric sulphide.[1] With this one exception, the synthetic material formed at higher temperatures is identical with natural chalcocite. Consequently it seems that there is little hope of distinguishing primary and secondary products by microscopic means, where both are in ordinary replacement relations to the bornite, and the lack of break between definitely recognized secondary chalcocite and the chalcocite associated with the graphic structures, as at Engels, cannot be regarded as a convincing argument against the primary origin of the latter.

Hypothesis of Selective Replacement. In the discussion of the properties of graphic structures on preceding pages, the features were emphasized, which oppose the hypothesis of simple replacement origin for the chalcocite. In resumé, the occurrence of chalcocite in the graphic structure often in the heart of bornite grains, the lack of dependence of the chalcocite on gangue boundaries, the abrupt termination of graphic areas against masses of bornite, and the contrast to the forms of ordinary replacement are difficult to explain as results of metasomatic processes and offer very serious objections to the hypothesis.

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1. Eugen Posnjak, E. T. Allen, H. E. Merwin, loc. cit.

On the other hand it will be recalled that there is fairly definite evidence that the development of chalcocite in many graphic structures was actually accompanied by replacement reactions. The microscopic evidence has already been summarized. There are a few cases in which the field evidence is significant. At Bisbee, Arizona,[1] and at Rising Star Mine, Shasta Co., California,[2] the chalcocite ores, in which the graphic structures occur, appear not to continue into the deepest workings. Although the deposits have not been examined with sufficient thoroughness to establish these observations as definitely as might be desired, the evidence is very suggestive that the chalcocite in the graphic structures is related to the distribution of secondary enrichment. At Butte, when the deepest known ores containing chalcocite and bornite in the graphic relation occur, definite observations, which will not be detailed here, make it apparent that from our present information, the possibility of the secondary alteration of bornite even at the great depths attained there cannot be eliminated.

If, however, the replacement hypothesis is to be made acceptable, it must be modified in such a way that it offers a competent explanation for the peculiar but particularly characteristic features of graphic structures, which are so suggestive of contemporaneous nature of the mineral

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1. See pages 173-174.
2. L. C. Graton, personal communication.

components. An explanation must be offered for the selective manner in which the bornite is attacked, in which the obvious lines of weakness are neglected and the advance of the chalcocite is directed into irregular yet fairly constant forms. To do this, the hypothesis may be suggested that bornite exists in two forms, one of which is slightly more resistant to the influence of enriching processes than the other. The difference between them is assumed to be sufficient to allow one form to remain unaltered under certain conditions of mild, probably long-continued attack of altering solutions, while the other is completely replaced. According to this hypothesis, the graphic structure would be explained as the result of selective replacement of the more easily altered type of bornite from a contemporaneous intergrowth of the two. The replacement relations usually associated with the structure could be readily considered to be slight modifications of the more resistant type, or less commonly incomplete replacement of the feebler type. As replacement tendencies became more and more intense, the resistant type would be expected to yield, and the earlier structure would be gradually obliterated.

This explanation harmonizes the conflicting evidence in a very complete way. The evidence of contemporaneous intergrowth structures may be accepted without modification, for they are attributed to the primary relations of the two bornites, and the evidence of replacement relations

between the bornite and chalcocite can also be taken without discount for a metasomatic origin is assigned to the chalcocite.

The conception of two bornites, of course, cannot be confined to the graphic structure alone, but must find support in features observed in other forms of bornite replacement. In the discussion of the lattice structure, the occurence of plates or splines, apparently more resistant than the surrounding material, was described. (Figures 143, 147, 148, and 149.) In these associations it is usually evident that the surrounding material had been altered to a chalcocite-bornite lattice with remarkable uniformity throughout the field, while the splines of bornite had been attacked only slightly or not at all. This relation when considered in the light of the new hypothesis, at once suggests that the splines of bornite are of the more resistant sort, while the main field was of the easily altered type. The relations in the lattice structure would indicate that widespread replacement of bornite by chalcocite in this pattern is probably confined to the less resistant bornite. The symmetrical relation of the splines to the surrounding lattice shows that the two bornites are either of the same or closely related crystal forms. In a few instances a slight development of chalcocite in the lattice form has been observed along the margins of the splines, and it is probable that the same structure exists

in them as in the surrounding field, but that it is less easily developed by the chalcocite.

Two forms of bornite associated in the graphic pattern would suggest contemporaneity in formation, but splines of the more resistant type surrounded by the easily altered sort would suggest an age difference which, however, might be only slight. Two interpretations may be offered for the second relation:

(1) that the splines were the earliest to form, probably as skeletal crystals, and that the angular spaces between them were filled later by the less resistant bornite, or

(2) that the easily altered type was the first to form, and was then altered to the resistant bornite by agencies which advanced along crystallographic planes, similar to the invading chalcocite at a later time.

In our present lack of knowledge concerning the possible nature of the differences between the two bornites, if such exist, further speculation is useless, but it may be suggested that since the earliest product to crystallize from a melt or solution is often the purest, as has been suggested by Dr. E. T. Allen, and since pure substances are usually more resistant to alteration than impure, the first interpretation is probably the better one.

The sharply defined spots and irregular blebs of bornite which remain as residues in chalcocite derived by lattice replacement, also indicate the existence of a more resistant type of bornite than that which had surrounded

them. Their clean boundaries, irregular forms and distribution place them in contrast to the usual angular residues produced by a lattice replacement. Their resemblance in some cases to forms of graphic structures suggests that the chalcocite of the latter may have been derived by lattice replacement.

Chalcocite occurring in the graphic relation in the heart of bornite grains has been mentioned. Similar cases in which the outer portions of grains are apparently more resistant than the cores have been observed in which the bornite in the centre is partially replaced by chalcocite in the lattice pattern (Fig.146)[1], which may be accepted as proof that the chalcocite is of metasomatic origin. The resistance of the bornite in the outer parts of the grains is probably to be explained in the same way as the survival of the splines, which has just been discussed. It is worthy of note in this connection that the centers of bornite grains on the polished surface frequently are strongly attacked by artificial reagents, whereas the marginal portions are more resistant.

The lattice structure as has been mentioned has been observed well developed throughout definite grains of bornite, yet sharply terminated against others which are

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1. J. Murdoch, Op. cit, Frontispiece, Fig. 2. It should be noted that the specimen illustrated is a crystal determined to be of proper bornite form. This removes the possibility that the outer rim of bornite is of later deposition.

apparently untouched by the chalcocite. The strips of chalcocite are cut off as regularly and as consistently as if against another mineral possessing complete resistance to their attack. This selective replacement is usually more apparent in the early stages of enrichment, but it has been seen in specimens in which chalcocite is the predominant member of the lattice. Such differential attack cannot be attributed to chance, and it seems to imply that there is a variation in the resistance of bornite which can direct and control the advance of chalcocite alteration in the early stages.

In ores from the Kotsina District, which have been described previously (page 241), the development of the secondary copper sulphides was found to leave certain irregular strips and bands of bornite untouched. The chalcocite and covellite seem confined to definite grains, but usually permeate the bornite thoroughly within these limits. They rarely assume the lattice pattern. In the zones resistant to chalcocite, however, chalcopyrite is developed sparingly, but in excellent lattice forms. If the theory of two bornites is applied, the relation indicates that both sorts are capable of yielding lattice replacements, an observation which finds confirmation elsewhere. The formation of chalcopyrite may be attributed to the accumulation of iron released by the replacement reactions which produced the chalcocite and covellite in the more easily al-

tered bornite.

On polished surfaces of ores from the Bonanza and Jumbo Mines, at Kennecott, angular, broken strips of bornite have been observed in chalcopyrite. When first examined, they at once give the impression that the bornite is in veins in the chalcopyrite and should therefore be considered to be of later age. If a strip, however, is traced into a bornite field, its continuation is usually marked by a delicate border of fine chalcopyrite spines, which gradually disappear and allow the "vein" to lose its identity in the massive bornite. (Fig. 123, 124, 148, and 154.) The summation of the evidence (page 259) presents such a strong case favoring the replacement of bornite by chalcopyrite, that it forces the belief that the bornite strips are not veins in the chalcopyrite, but residues, which for some reason remain resistant to chalcopyrite attack, as do the splines in the lattice structure to the chalcocite attack.

Direct evidence indicating two types of bornite, however, is not abundant or especially significant. There is a slight variation in the hardness of different grains or different parts of the same grain in some cases, which is shown most definitely by the relief on the polished surface. Variations of this sort may possibly be attributed to changes in properties due to crystallographic orientation but not very probably for the mineral is isometric. Harder rims about softer cores have been observed in material from the

Kuskulana District, Alaska,[1] but in no cases have the hard and soft types been found associated in forms similar to graphic patterns. An array of arguments against the view of two types of bornite may be raised, but none of very positive or final character. The color of bornite on the freshly polished surface is very constant.[2] Slightly yellowish tints have been observed, but it is most probable that they are due to submicroscopic spines of chalcopyrite, and not to any variation in the character of the bornite. The etch-patterns of bornite offer no evidence of two types possessing different properties. The cracks are either of the regular sort within the limit of the grain, or evenly irregular in a way which carries no significance. Stripe with a slight variation in pattern have been observed in a very few cases, and may possibly be related to the splines but the orientation of the cracks suggests that the structure is probably due to twinning. Bornite from different districts often shows a distinct variation in vigor of reaction with the ordinary reagents, but the character of the reaction seems to be constant within a limited field, as far as our experience goes. The regional variation may be due to purely physical characters, such as porosity, or the presence of submicroscopic impurities.

The constant chemical character of natural bornite

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1. A. Wandke, personal communication.
2. J. Murdoch, Op. Cit., p. 35.

may be regarded as established with certainty and there is little likelihood that true variations in composition occur. In work done in the Geophysical Laboratory,[1] which will soon be published, bornite was found to possess no inversion points, such as the one between isometric and orthorhombic forms of chalcocite at 91°. As far as the properties of bornite are known at present, there is no definite physical or chemical evidence to indicate that it possesses more than one form.

A rather serious objection which may be raised against the hypotheses of selective replacement is that no partial stages of the metasomatic changes have been observed with certainty. Bornite residues, in the lattice pattern in some cases, should be found in the chalcocite blebs and lobes of the graphic structure according to the mechanism suggested, but in general they are completely absent. Indications of residual bornite strips have been found in two or three cases, but the evidence is hardly definite enough to settle the matter, and although it lessens the weight of the objection, it does not remove it. Chalcocite which has been formed by the lattice replacement of bornite usually possesses a triangular etch-pattern; the chalcocite in the graphic structures commonly yields the orthorhombic etch-cleavage. (Fig.136.) Consequently it is improbable that the chalcocite in the

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1. Private communication.

1 Tritia communis.

graphic relation with bornite was derived by a replacement of the lattice type, which greatly weakens the force of one attractive explanation according to the hypothesis of selective replacement.

Summary and Conclusion

The relations of the chalcocite and the bornite in all graphic structures cannot be satisfactorily explained either by the hypothesis that the two minerals are of strictly contemporaneous origin or by the view that the chalcocite is produced by simple replacement of bornite of ordinary homogeneous character. Normal replacement origin will apparently not account for any of the graphic structures. Strictly contemporaneous origin will account for many.

If the hypothesis of contemporaneous origin is modified to the extent that it allows replacement conditions of bornite by chalcocite to follow upon the heels of contemporaneous deposition, it becomes more acceptable, and affords a satisfactory explanation for nearly all the observed features. The chalcocite fits into the later phases of the sequence of primary minerals in a logical manner and chemical knowledge of its properties and range of stability offers no objections to its being placed there. Opposed to the view is the difficulty of finding any break between secondary chalcocite and that closely and intimately associated with the graphic structure. In two districts, the apparent

dependence of chalcocite in the graphic structure on the distribution of the secondary sulphides is also of opposing nature, but more careful field and laboratory studies are required before the strength of the last argument can be fully established. If it is upheld by more detailed work, it offers a serious objection to the hypothesis of primary chalcocite.

The explanation based on selective replacement depends on the strong evidence of the importance of metasomatism in close association with the graphic structure, and the apparently greater resistance of bornite in certain forms to alteration. It finds support in the satisfying way that it harmonizes conflicting evidence of contemporaneous and replacement structures, and in the many features in other structures which suggest two types of bornite, such as splines, rims, resistant specks and abrupt terminations. It is seriously weakened by the lack of known chemical or pronounced physical variations in the properties of bornite, and by the rareness of any forms which may be interpreted as intermediate stages in the replacement.

Of the four possibilities which have been suggested, viz. strictly contemporaneous deposition, modified contemporaneous depostiion, selective replacement and normal replacement, it is noteworthy that the first three agree in assuming that the graphic pattern is controlled by a primary structure in the ore, and each of these ideas has something

to commend it, whereas the fourth hypothesis which assumes no prior control, finds no positive support from any of our observations.

The importance of the solution of the problem is not to be minimized, for, if either hypothesis of contemporaneous origin can be accepted, it establishes the existance of primary chalcocite; if they are discarded, the chief argument favoring the primary nature of the chalcocite in many deposits (such as Engles for example) is lost, and the assumption of two ages of chalcocite becomes unwarranted.

It is apparent from the evidence and arguments advanced that none of the hypotheses can yet be accepted without reservation nor can either one of them except that of normal replacement be eliminated from the field. Neither is it certain that any one affords the sole explanation of the graphic structure. If the relative values of the different arguments could be established, the question would be easy to settle, but in the present state of our knowledge, this is difficult to do. With the constantly increasing mass of information which is being made available from geological and chemical work, however, it is quite probable that before long a closer appraisal of the evidence may be made and a final answer given, but at present, the wiser course is to leave the problem open.

The question of the origin of the graphic structure, although perhaps the most fascinating and puzzling encountered,

is merely one of the many problems which seek to conceal themselves behind the intricate structures and varied behavior of bornite, toward the solution of which this contribution has been directed.

MICROPHOTOGRAPHS

OF

ROCKS AND ORES

PLATE XIV

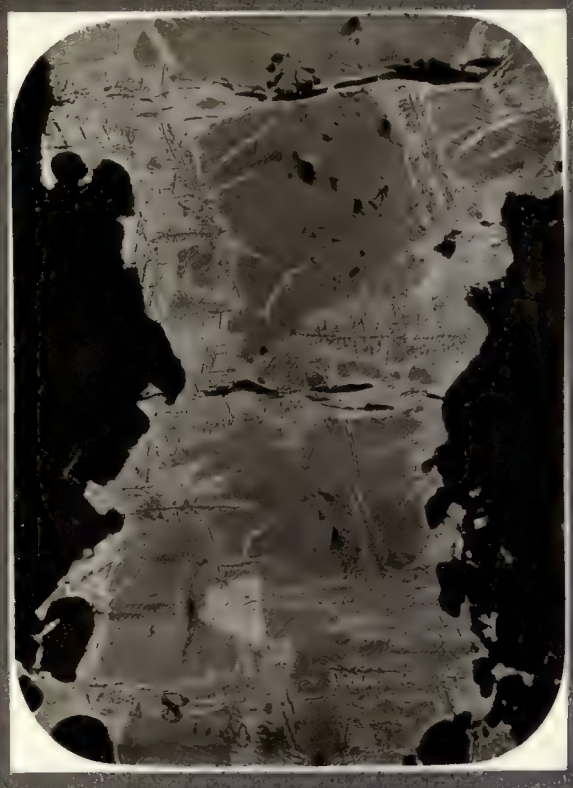
Photographs of Polished Surfaces of Ores from the Evergreen Mine, Colorado.

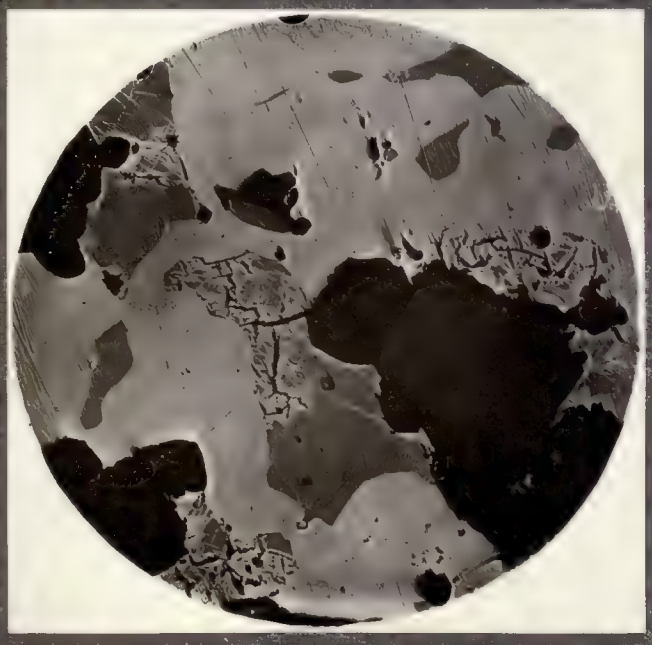
Fig. 41. (x 80 diameters) Bornite (gray), partially replaced by chalcocite (light), working in from gangue (black) contacts. The feathery material in fine lattice orientations in the chalcocite consists of very fine-grained chalcopyrite, and a little bornite, with some oxidized material. For discussion see page 75. A grain of chalcopyrite (light) in the lower part of the field remains resistant to the chalcocite.

Fig. 42. (x 80 diameters) Chalcopyrite (light) and bornite (dark). In part associated with mutual boundaries and in part in relations indicating replacement of chalcopyrite by bornite. Some spines of secondary chalcopyrite penetrating the bornite from gangue (black) contacts.

Fig. 43. (x 80 diameters) Primary chalcopyrite (light; cp_1) and bornite (dark) with mutual boundaries. Bornite partially replaced by secondary chalcopyrite, in imperfect lattice structures, accompanied by shrinkage cracks.

Fig. 44. (x 80 diameters) Bornite (gray) with a little primary chalcopyrite (light; cp_1) in smooth grains and more abundant secondary chalcopyrite (cp_2) developing at the expense of the bornite as rims along gangue veinlets, or as imperfect lattices.





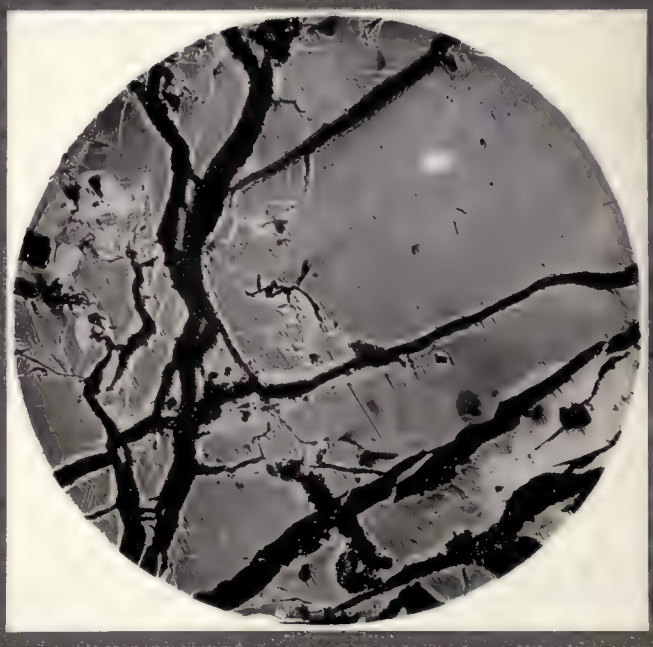


PLATE XV

Photographs of Polished Surfaces.

Fig. 45. (x 50 diameters) Evergreen Mine, Colorado. Bornite (dark) and chalcopyrite (light) in graphic association. Secondary chalcopyrite developed in bornite bleb in upper portion of the field. Note shrinkage cracks.

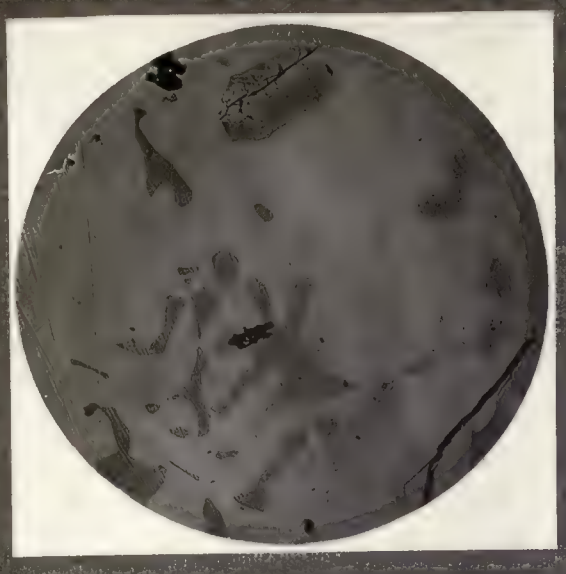
Fig. 46. (x 50 diameters) Evergreen Mine, Colorado. Bornite (dark) both in graphic structures with chalcopyrite along gangue veinlets (black).

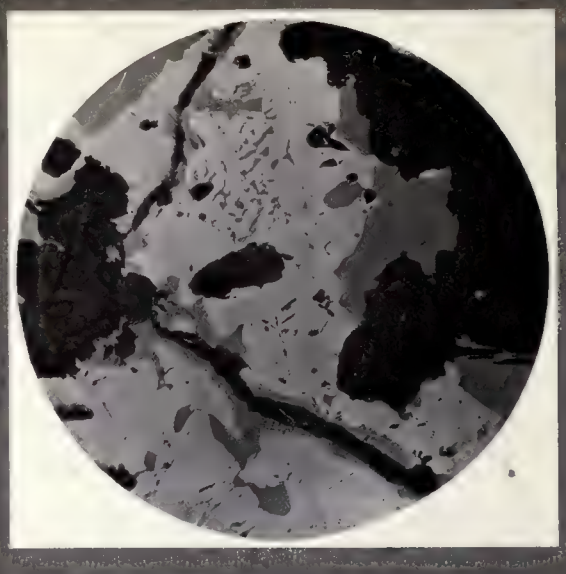
Fig. 47. (x 50 diameters) Evergreen Mine, Colorado. Bornite (dark) both in mutual relations with chalcopyrite (light) and as a replacement of chalcopyrite in definite veinlets.

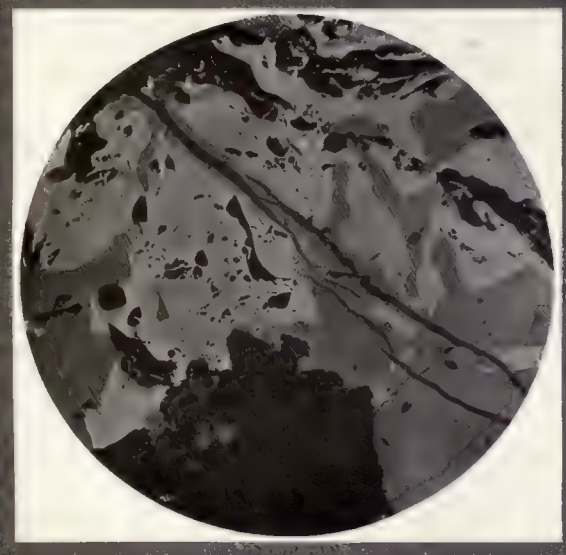
Fig. 48. (x 50 diameters) Evergreen Mine, Colorado. Bornite (dark) in mutual relations toward primary chalcopyrite (light) and partially replaced by secondary chalcopyrite, in the lattice structure.

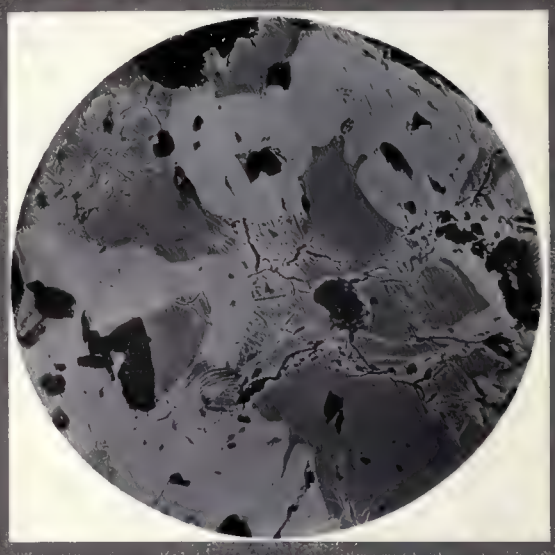
Fig. 49. (x 50 diameters) Marble Bay Mine, Texada Island, B. C. Bornite (gray) with an intermittant border of klaprotholite (?) (white), and chalcocite, and chalcocite (light gray). Gangue, black.

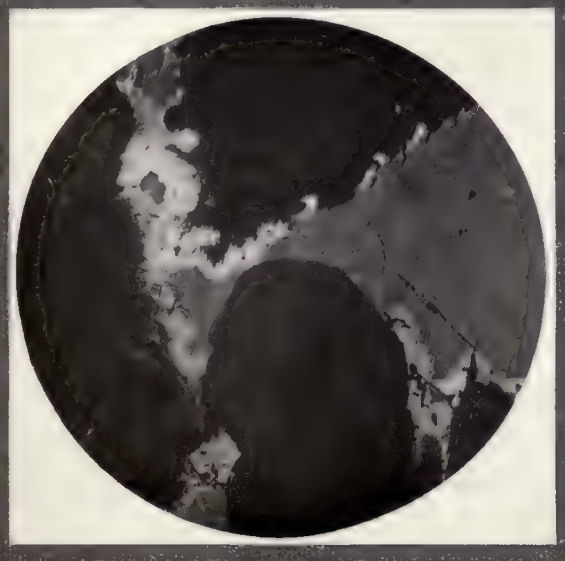
Fig. 50. (x 48 diameters) Marble Bay Mine, Texada Island, B. C. Chalcopyrite (light) and bornite (dark) in primary relations which slightly suggest the earlier age of the chalcopyrite.











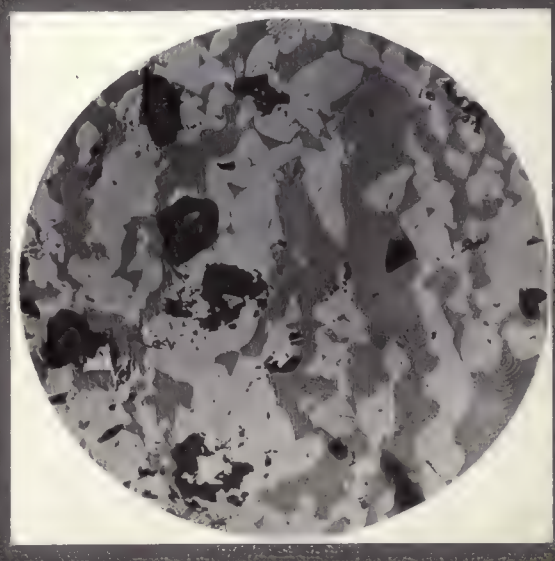


PLATE XVI

Photographs of Thin Sections of Rocks and Ores from Engels, California.

Fig. 51. (x 20 diameters) Bornite (black) replacing rock-minerals, with only slight development of chlorite and epidote.

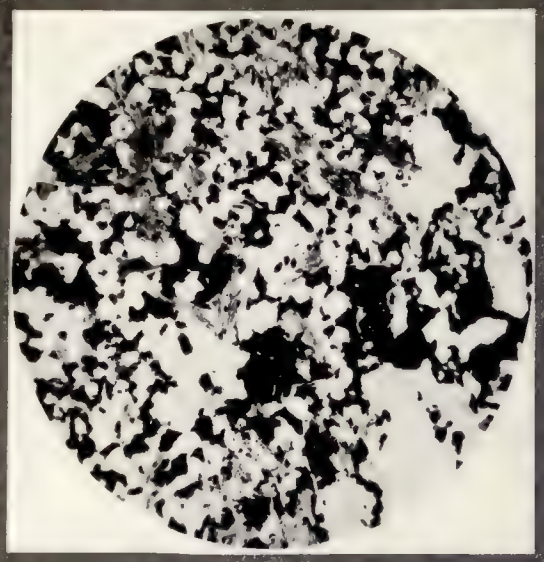
Fig. 52. (x 90 diameters) Crossed nicols. Broken apatite prism in strained feldspar.

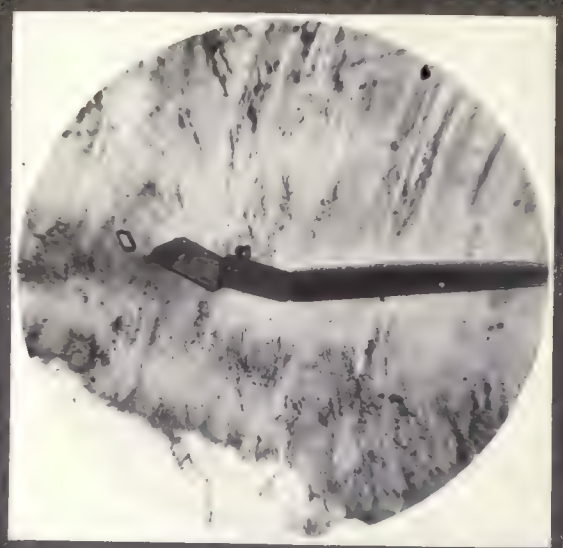
Fig. 53. (x 13 diameters) Crossed nicols. Feldspar phenocryst in granodiorite porphyry, showing recrystallization.

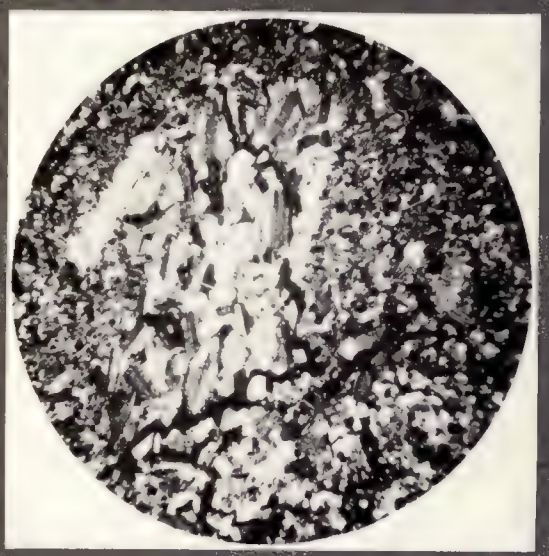
Fig. 54. (x 20 diameters) Same as in figure 53, but without crossed nicols.

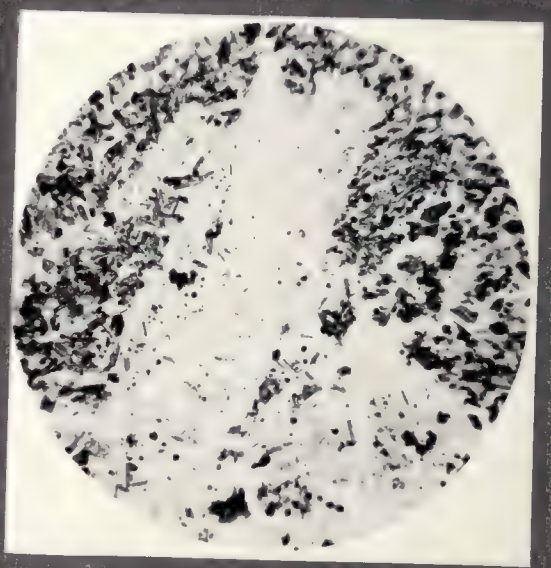
Fig. 55. (x 16 diameters) Poikilitic hornblende, with feldspar and magnetite chiefly.

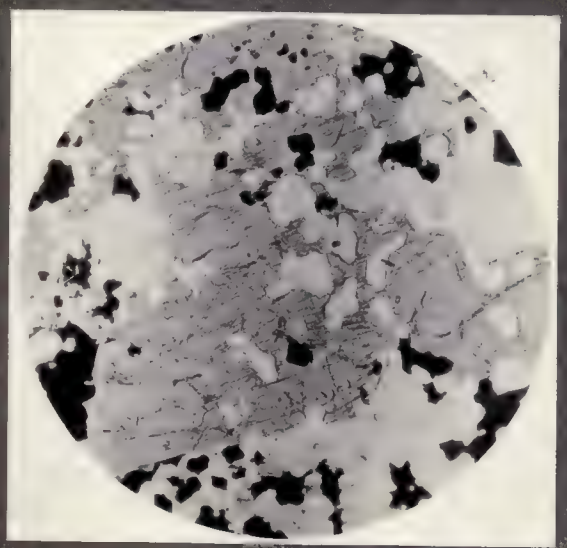
Fig. 56. (x 32 diameters) Euhedral epidote crystals included in bornite.











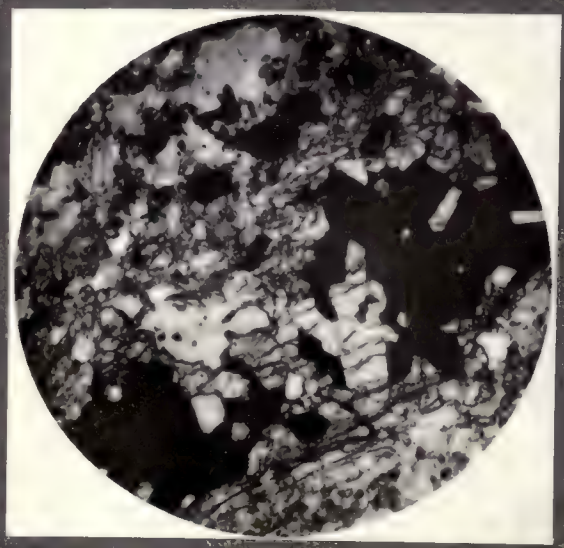


PLATE XVII

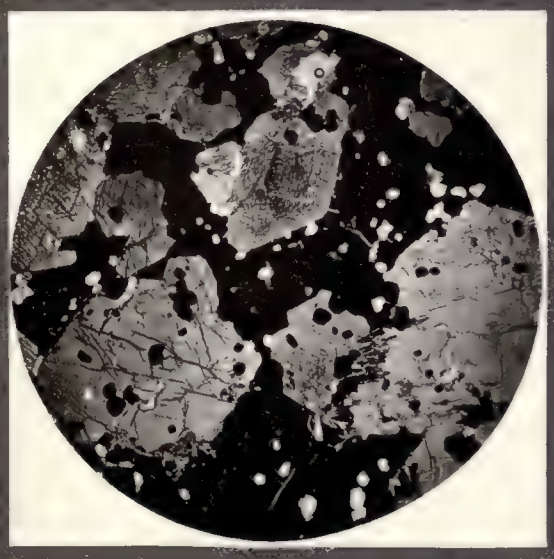
Photographs of Thin Sections of Rocks and Ores from Engels, California.

Fig. 57. (x 65 diameters) Hornblende crystal surrounded by magnetite and corroded by chlorite and bornite. Chlorite also in thin folds between magnetite grains.

Fig. 58. (x 52 diameters) Magnetite and bornite with chlorite along boundaries of magnetite grains.

Fig. 59. (x 52 diameters) Hornblende crystals containing small inclusions of magnetite and spinel (spn.), and corroded by surrounding magnetite. Note abundant inclusions of apatite in the magnetite, and the occurrence of bornite in ragged grains with chlorite.

Fig. 60. (x 65 diameters) Bornite and chlorite replacing amphibole. Magnetite in smoother grains.



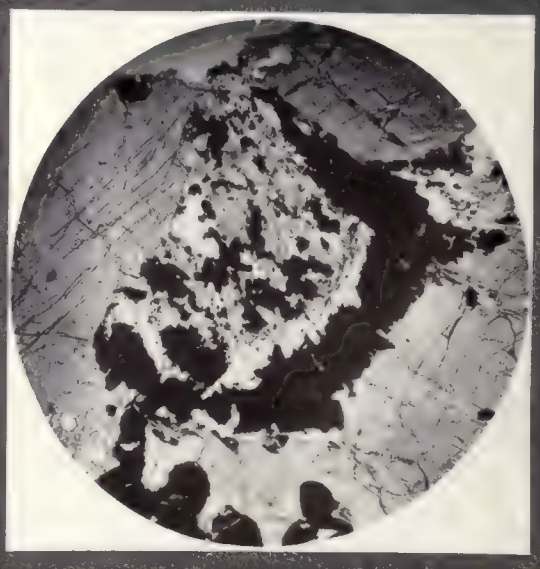


PLATE XVIII

Photographs of Ores from Engels, California.

Fig. 61. (x 30 diameters) Thin section. Hornblende partially replaced by calcite, developed along cleavages of the former.

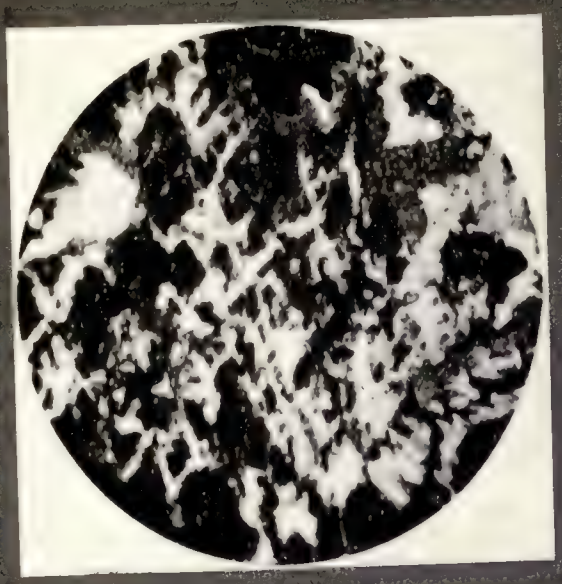
Fig. 62. (x 54 diameters) Thin section. Crossed nicols. Plagioclase partially replaced by heulandite (heu.), and both partially altered to natrolite (white).

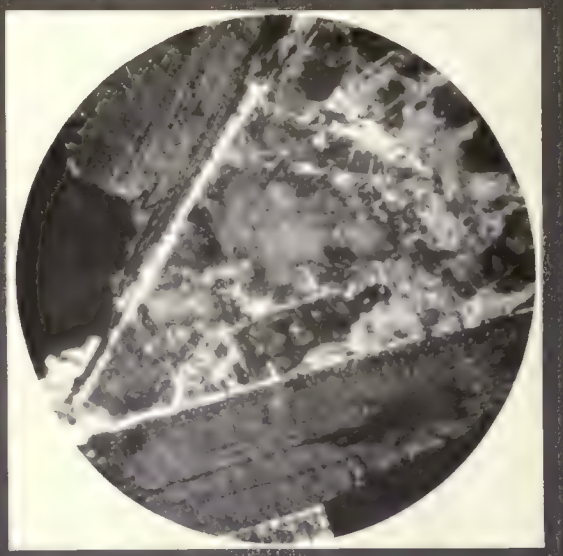
Fig. 63. (x 44 diameters) Thin section. Epidote veinlets cutting albite and chlorite. Also patches of epidote.

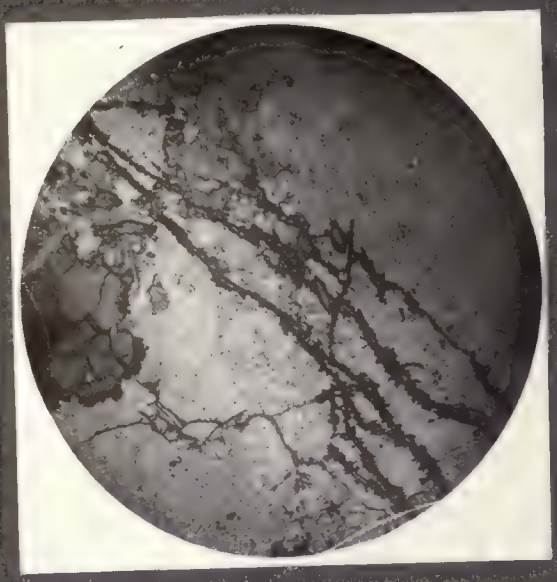
Fig. 64. (x 50 diameters) Polished section. Bornite (white) with inclusions of chlorite (dark laths); magnetite (gray), earlier than the bornite.

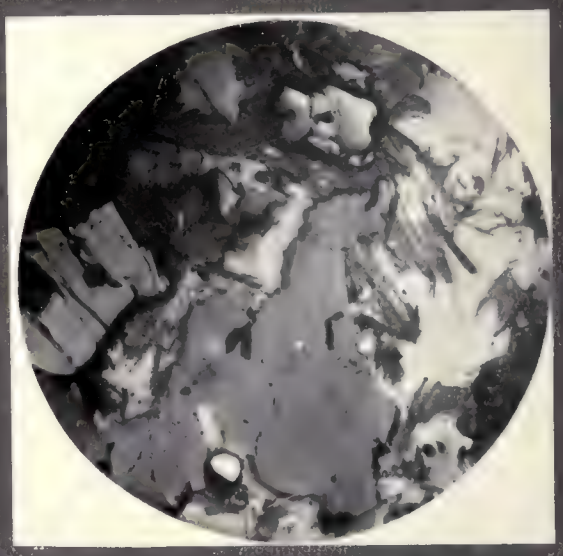
Fig. 65. (x 65 diameters) Thin section. Ore-bearing diorite cut by siderite (?) veinlets.

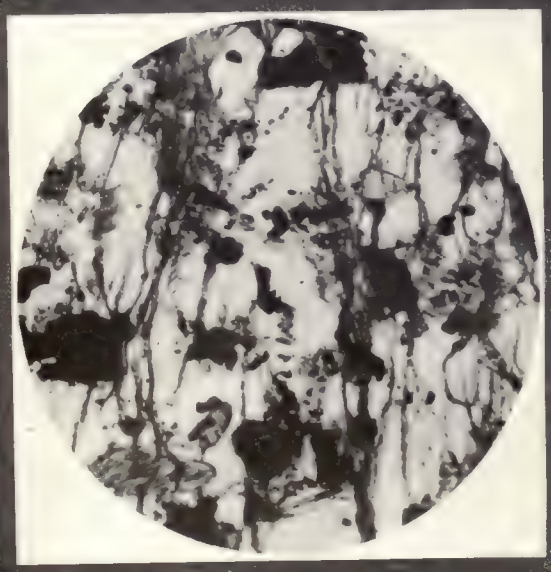
Fig. 66. (x 650 diameters) Polished section. Chlorite (dark) corroded by bornite.











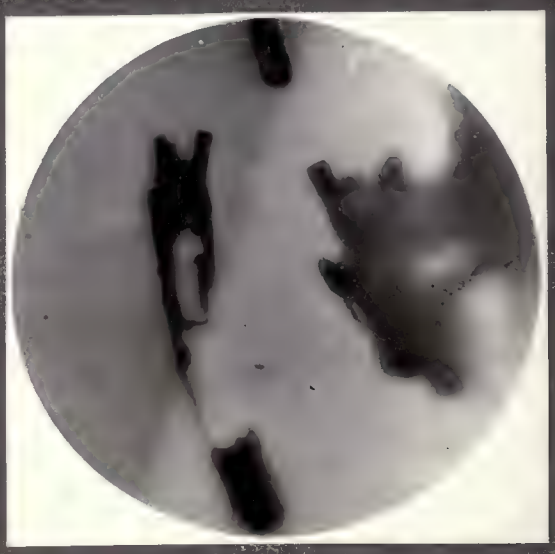


PLATE XIX

Photographs of Polished Surfaces of Ores from Engels, California.

Fig. 67. (x 74 diameters) Chalcopyrite (dark) and bornite (light) with mutual boundaries. Gangue, black.

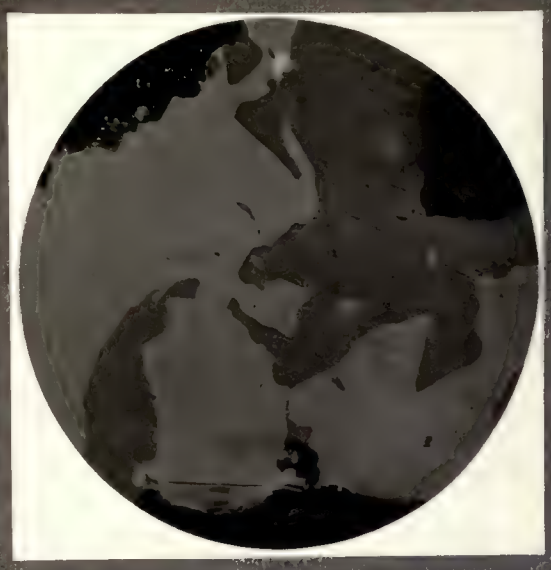
Fig. 68. (x 50 diameters) Bornite (grey) with chalcocite (light) developed along chlorite (dark) inclusions in the bornite, and along gangue veinlets.

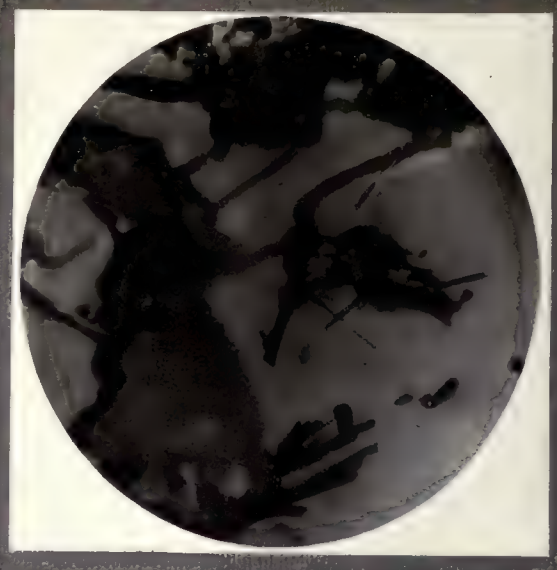
Fig. 69. (x 60 diameters) Bornite (dark) with chalcocite (light) both in graphic associations (upper part of the field) and in veinlets, in part along gangue (black) contacts.

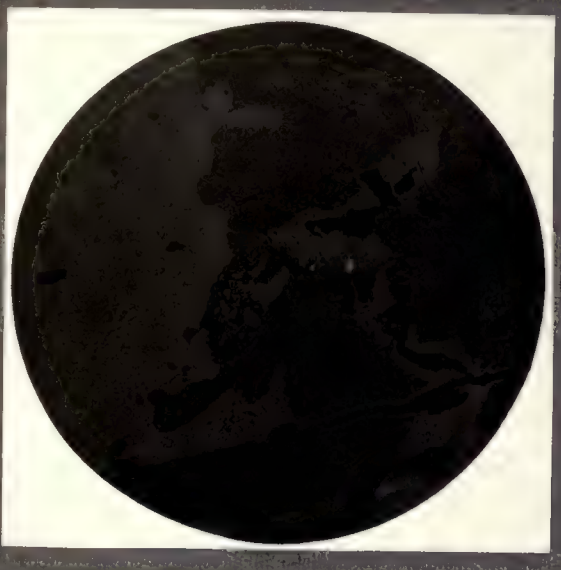
Fig. 70. (x 70 diameters) Bornite (dark) with chalcocite (light) mostly in graphic structures. Note the extension of bornite through the field along the intermittant line of gangue (black), with chalcocite along the centre of the bornite zone.

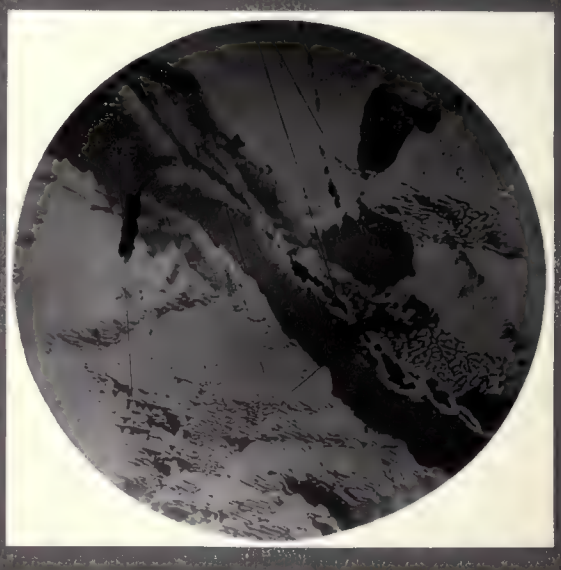
Fig. 71. (x 250 diameters) A portion of the field of Fig. 70.

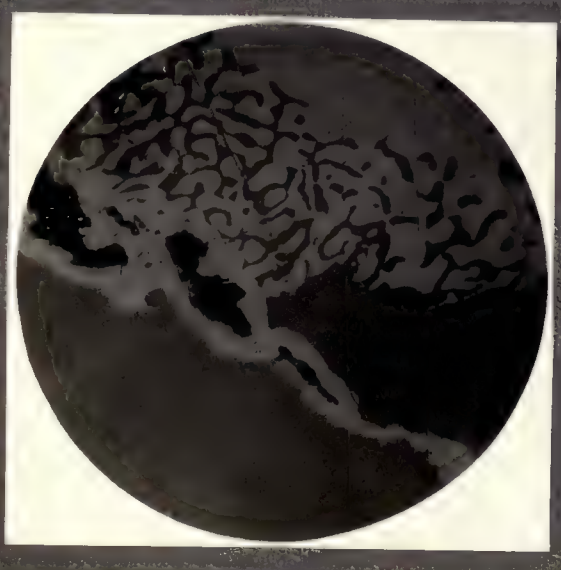
Fig. 72. (x 650 diameters) A portion of the field of Fig. 70. Bornite, dark; chalcocite, light.











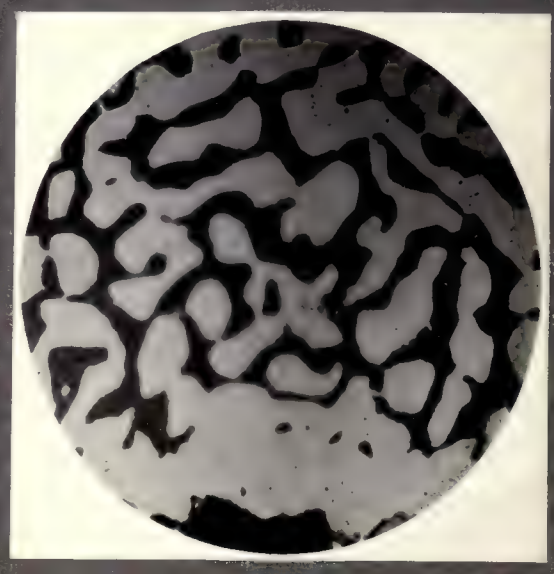


PLATE XX

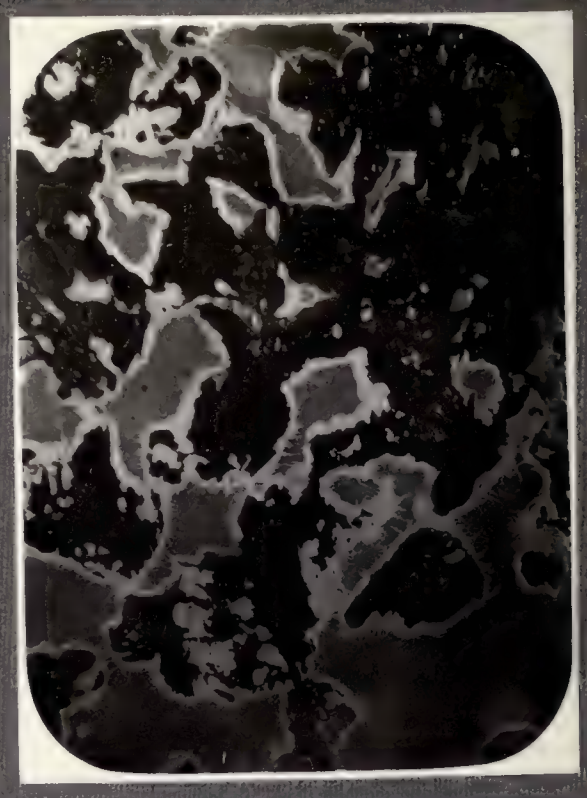
Photographs of Polished Surfaces of Ores from Engels, California.

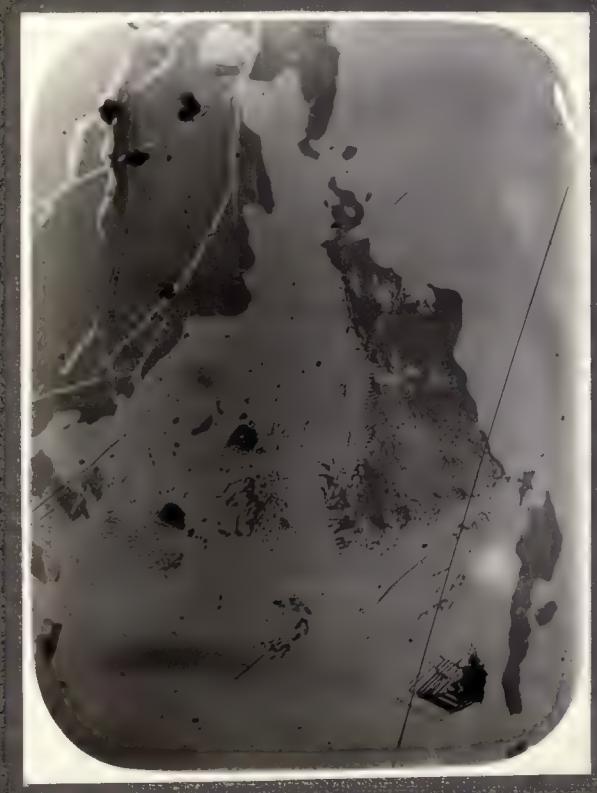
Fig. 73. (x 80 diameters) Veinlets and patches of chalcocite (light) in bornite (dark) in part along gangue veinlets (black). Note subgraphic form of some of the larger chalcocite grains.

Fig. 74. (x 70 diameters) Bornite grains (dark) with rims of chalcocite (light) in altered diorite (darker gray). Note the imperfect beginnings of a lattice structure between the bornite and chalcocite in many places.

Fig. 75. (x 70 diameters) Bornite (dark) with chalcocite (light) both in graphic structures and in veinlets in the bornite. Note cleavage cracks in the chalcocite about holes in the polished surface.

Fig. 76. (x 280 diameters) Field of chalcocite (white) cut by a gangue veinlet (carbonate; black), with bornite in intermittant strips along the margin in the chalcocite.





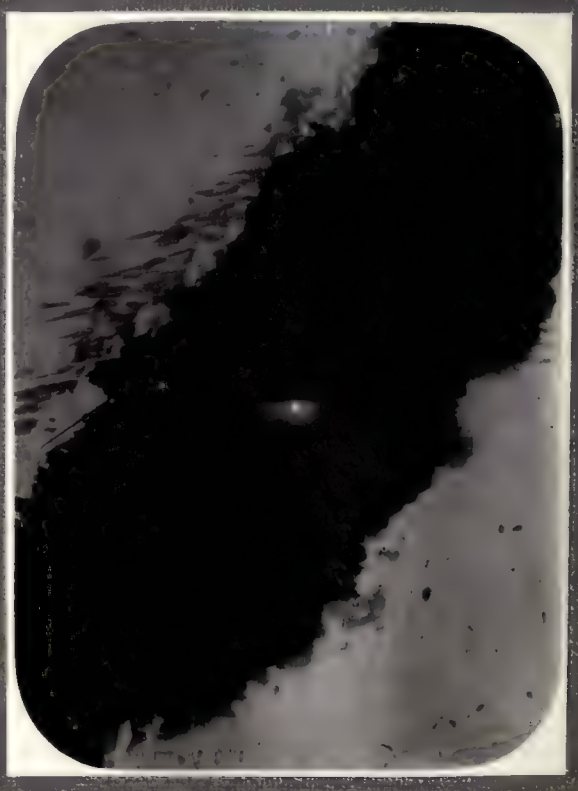


PLATE XXI

Photographs of Polished Surfaces of Ores from Engels, California.

(Photographs on this page by W. L. Whitehead.)

Fig. 77. (x 50 diameters ?) Bornite (dark) cut by lattice of chalcopyrite (light). Gangue, black.

Fig. 78. (x 900 diameters) Lattice structure developed in bornite (bn) by chalcopyrite spines (cp) with chalcocite rims (cc).

Fig. 79. (x 300 diameters ?) Bornite (dark) and chalcocite (light) in graphic structure.

Fig. 80. (x 1000 diameters) Photograph at higher magnification of portion of the same bornite-chalcocite graphic structure as shown in Fig. 79. Note that the chalcocite is dark and the bornite is light, due to a different color screen used in this case. The similarity in appearance of the two photographs in spite of this change is a striking example of the mutual relations of the two minerals.

PLATE XXII

Photographs of Polished Surfaces of Ores from Engels, California.

Fig. 81. (x 230 diameters) Bornite (dark) and chalcocite (light) in a fine-grained graphic structure. A portion of the field shown in Fig. 75.

Fig. 82. (x 250 diameters) Chalcocite (light) in graphic structure, rear edge of bornite grain (dark), and also associated with bornite in veinlets and along gangue contact.

Fig. 83. (x 250 diameters) Intergrowth of magnetite (light) and ilmenite, in which the latter is largely altered to leucoxene (gray). A little hematite (white).

Fig. 84. (x 70 diameters) Superior Mine, Engels, California. Magnetite grains (shadowed, due to high relief) set in a field of bornite (dark) with chalcocite (light) in graphic associations.

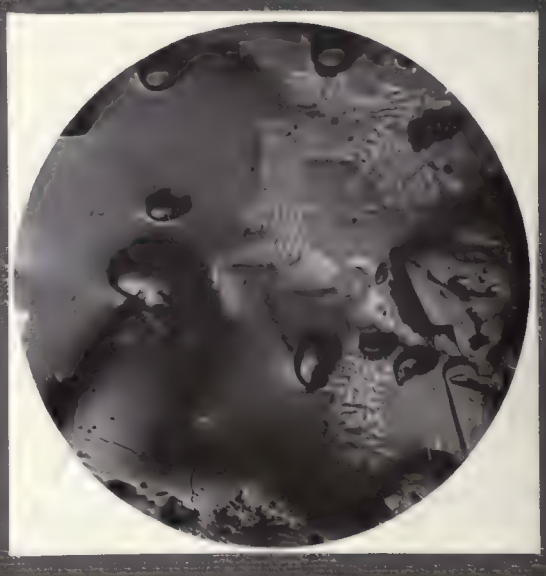


PLATE XXIII

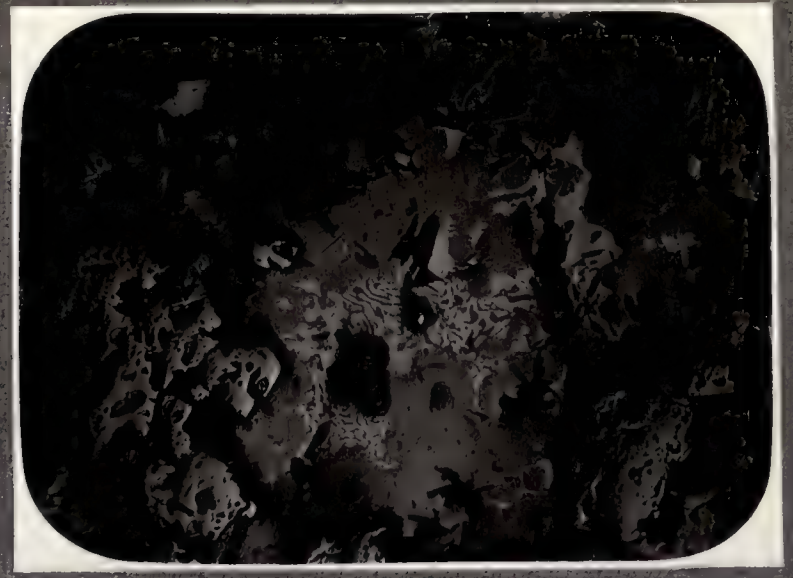
Photographs of Polished Surfaces of Ores from the Superior Mine, near Engels, California.

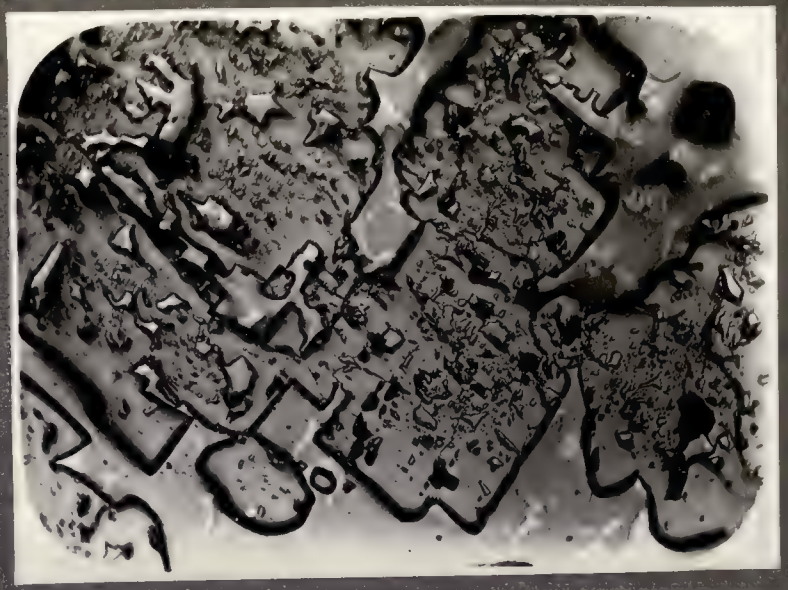
Fig. 85. (x 70 diameters) Magnetite crystals, shown by black borders due to high relief, surrounded by bornite (dark) containing blebs of chalcocite (light) suggesting imperfect graphic structures (subgraphic structures).

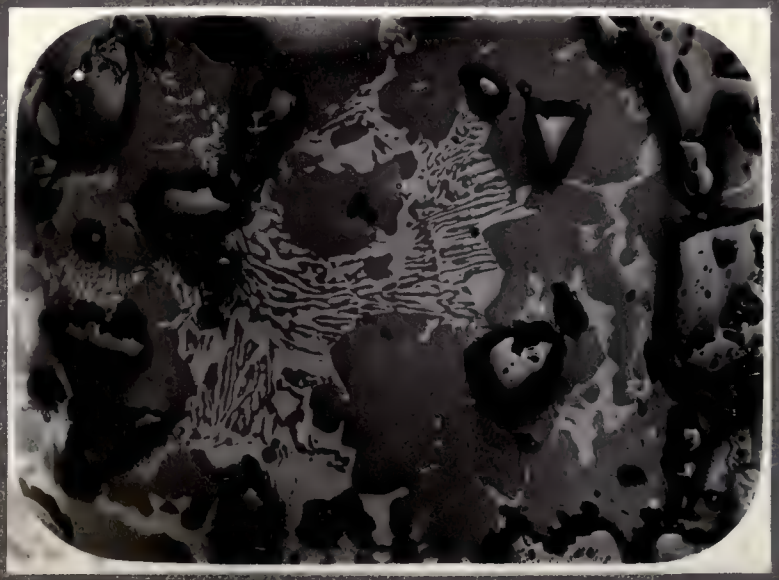
Fig. 86. (x 70 diameters) Magnetite grains, shown by black borders, with small inclusions of bornite, and surrounded by bornite containing chalcocite in graphic forms. Inclusions of chlorite in the bornite. Note lack of dependence of the chalcocite on margins of the bornite areas or on chlorite inclusions.

Fig. 87. (x 70 diameters) Similar to Fig. 86.

Fig. 88. (x 70 diameters) Bornite (dark) with chalcocite light in graphic structure. Magnetite grains, shown by high relief.







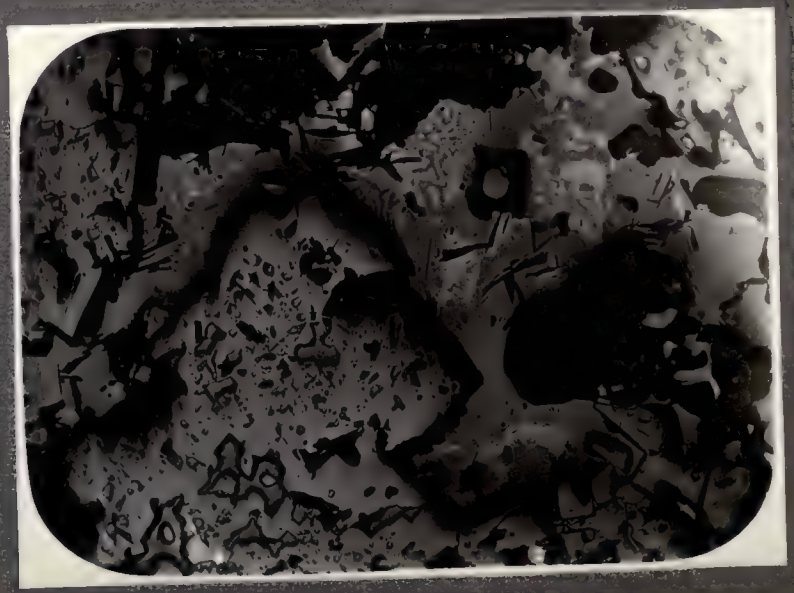


PLATE XXIV

Photographs of Polished Surface of Ores from the Magma Mine, Superior, Arizona.

Fig. 89. (x 250 diameters) Bornite (dark) in graphic structure with galena (white). Tetrahedrite (td), light gray.

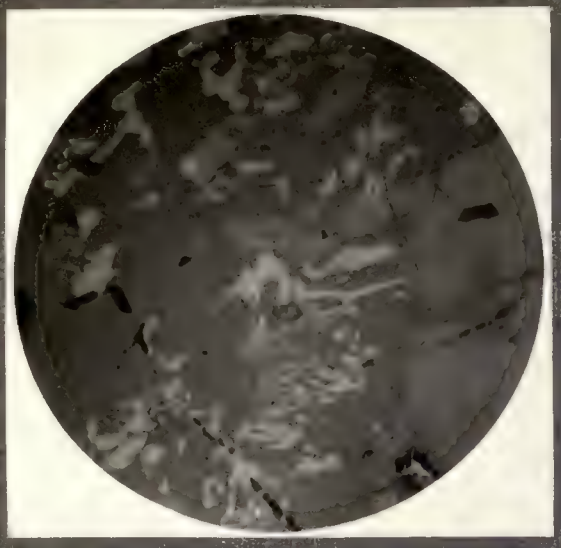
Fig. 90. (x 250 diameters) Similar to Fig. 89. Note great range in size of galena grains.

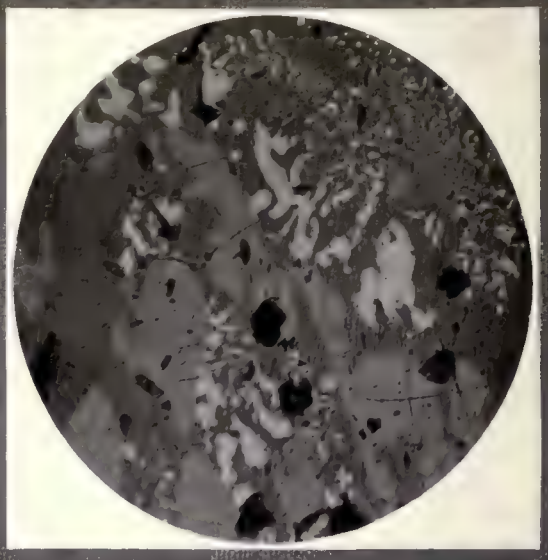
Fig. 91. (x 45 diameters) Chalcopyrite (white) and bornite (a very light gray) broken by later gangue minerals (quartz in part).

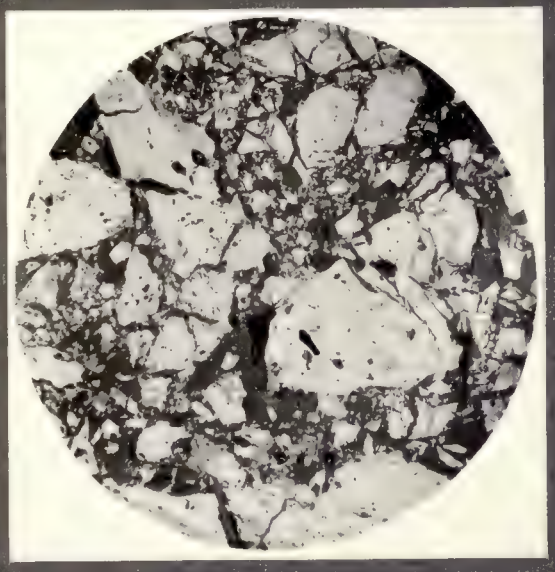
Fig. 92. (x 45 diameters) Bornite (dark) and chalcopyrite (light) in vein-like stringe of elongated blebs, often around bornite grains. (The variations in shade of the bornite are due to stains on the plate).

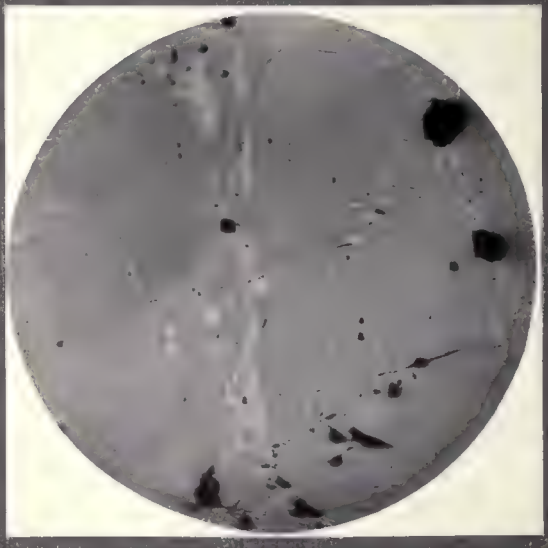
Fig. 93. (x 45 diameters) Pyrite (rough) broken by veinlets of bornite (smooth).

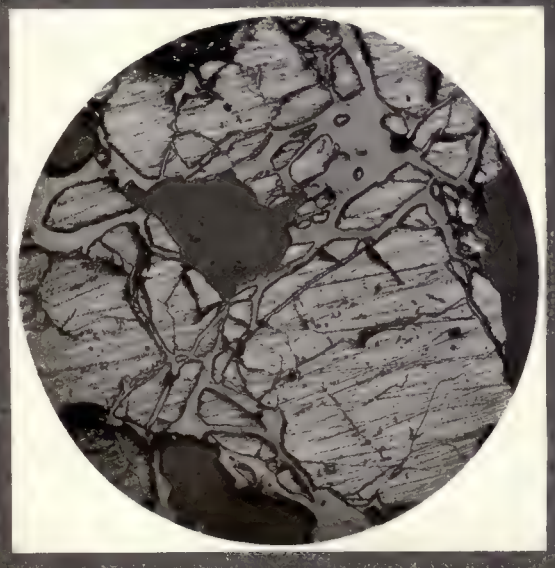
Fig. 94. (x 45 diameters) Pyrite (rough) broken by veinlets of bornite (darker and smooth). A primary replacement.











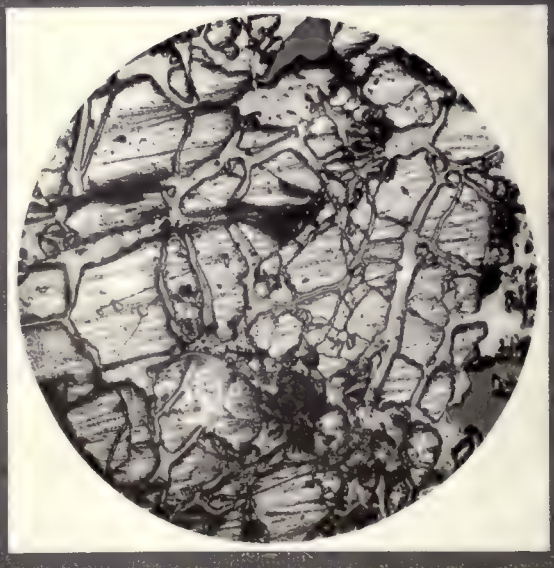


PLATE XXV

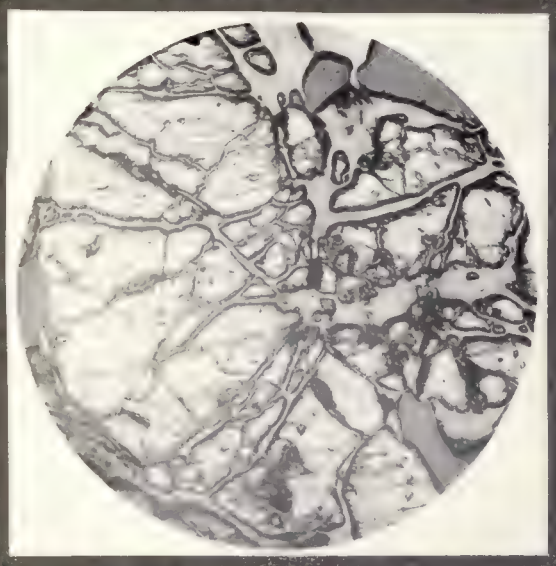
Photographs of Polished Surfaces of Ores from the Magma Mine, Superior, Arizona.

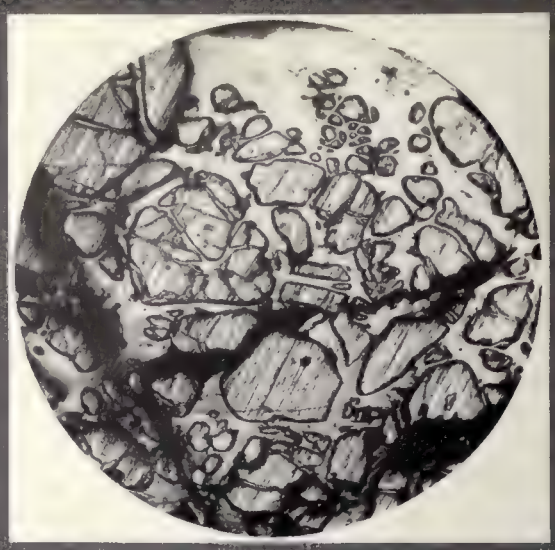
Fig. 95. (x 45 diameters) Pyrite grains broken by bornite veinlets.

Fig. 96. (x 45 diameters) Pyrite grains broken by bornite veinlets. Replacement of pyrite more advanced than in figures 93 and 94.

Fig. 97. (x 250 diameters) Chalcocite etched with nitric acid, revealing grained structure and orthorhombic nature, shown by the one set of strong cracks in each grain.

Fig. 98. (x 80 diameters) Chalcocite (light) with covellite (dark).





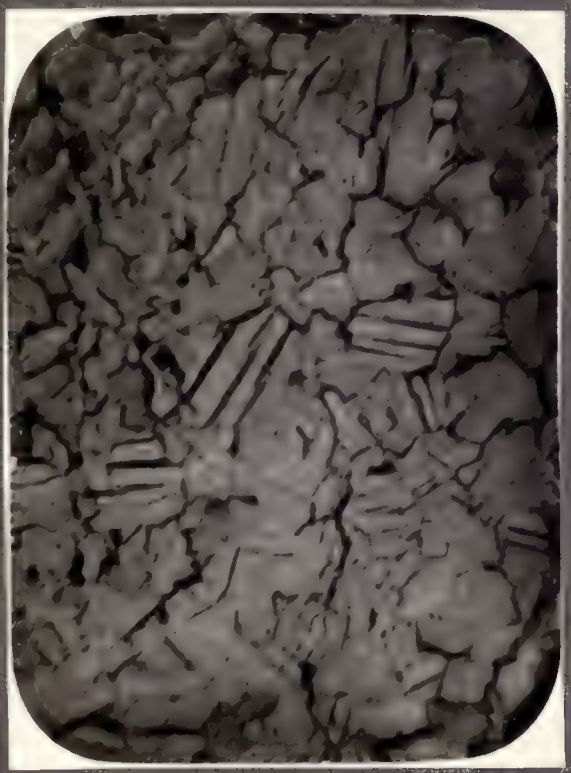


PLATE XXVI

Photographs of Polished Surfaces of Ores from the Kuskulana-Kotsina and the Kennecott Districts, Alaska.

Fig. 99. (x 50 diameters) From Nugget Creek, Kuskulana District. Bornite (dark) and chalcopyrite (light) in mutual relations, but with a suggestion that the bornite is somewhat later than the chalcopyrite.

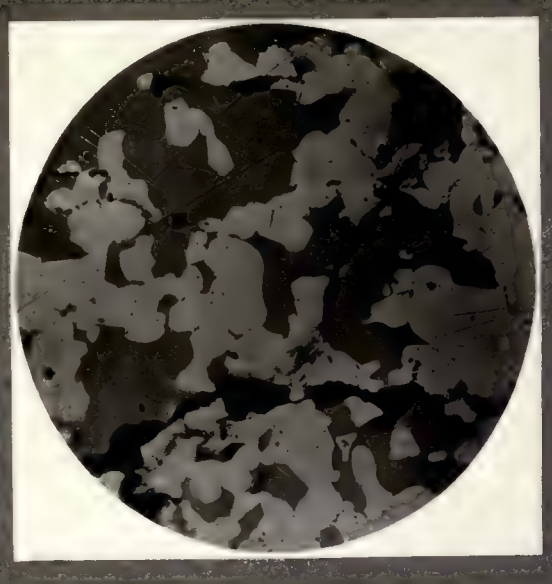
Fig. 100. (x 50 diameters) From Elliot Creek, Kotsina District. Chalcopyrite (light) corroded by bornite (dark).

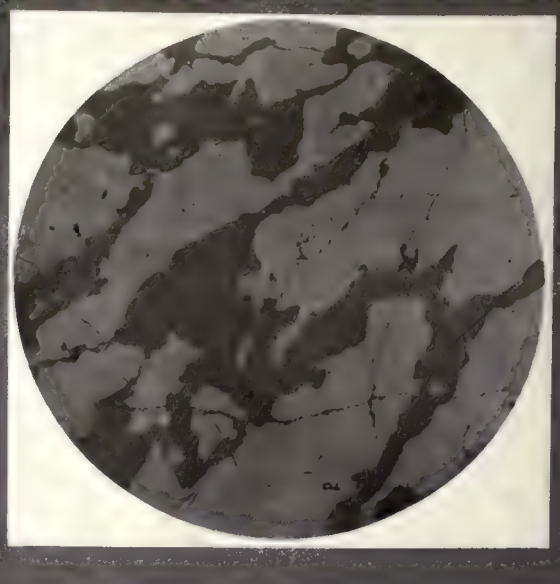
Fig. 101. (x 50 diameters) Nugget Creek. Bornite, (gray) and chalcocite (white), in subgraphic relations. Note lack of dependence of chalcocite distribution upon calcite (dark gray) contacts.

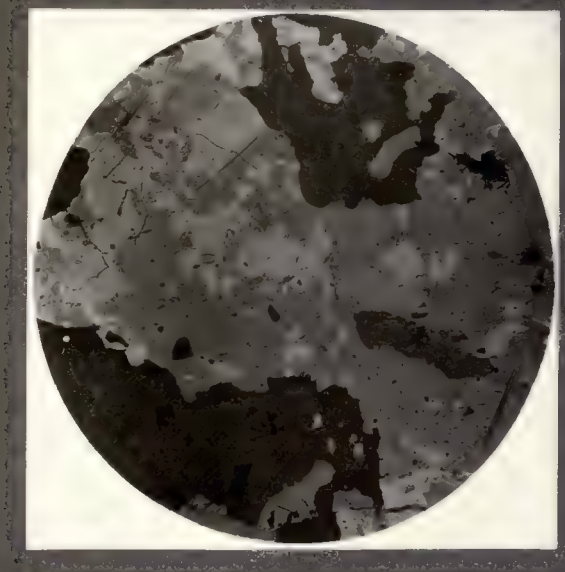
Fig. 102. (x 50 diameters) Nugget Creek. Bornite (dark) with chalcocite (light) in structures similar to those often shown between chalcopyrite and similar to those often shown between chalcopyrite and bornite; associated in one small area in the graphic structure.

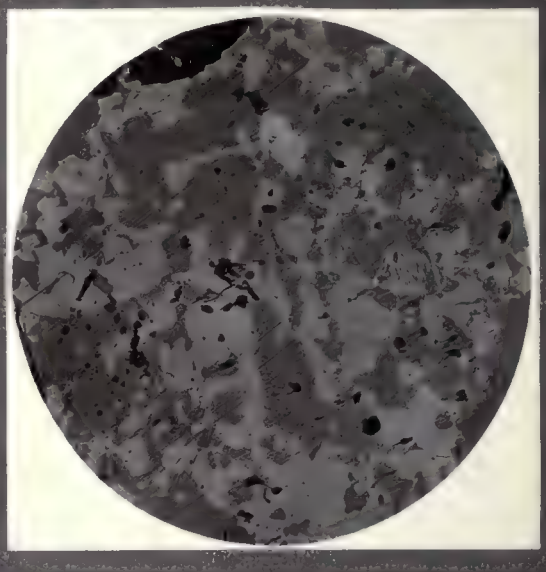
Fig. 103. (x 50 diameters) Bonanza Mine. Kennecott. Chalcocite (light) altering to malachite (dark) along structural planes. A little covellite (intermediate gray) between malachite and chalcocite.

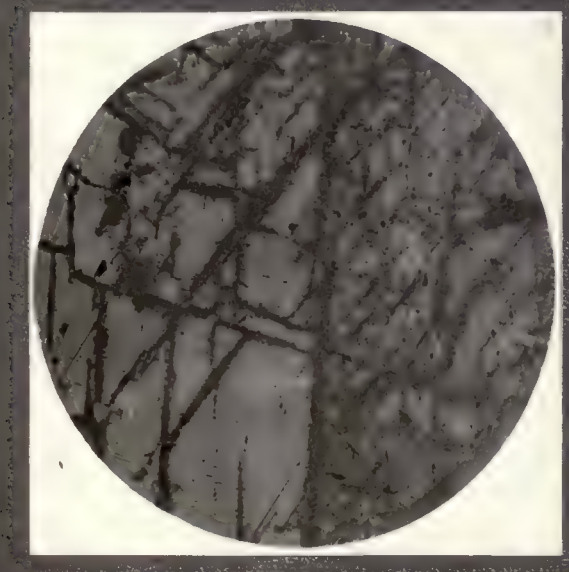
Fig. 104. (x 50 diameters) Chalcocite from a vein in the greenstone near the Bonanza Mine, Kennecott. Partially altered to malachite, along parallel lines revealing the orthorhombic structure. Compare with figure 103 in which the chalcocite develops the triangular pattern, believed to be isometric.

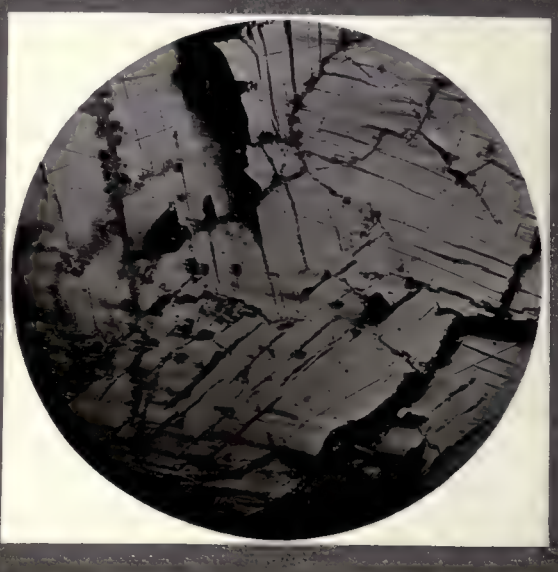












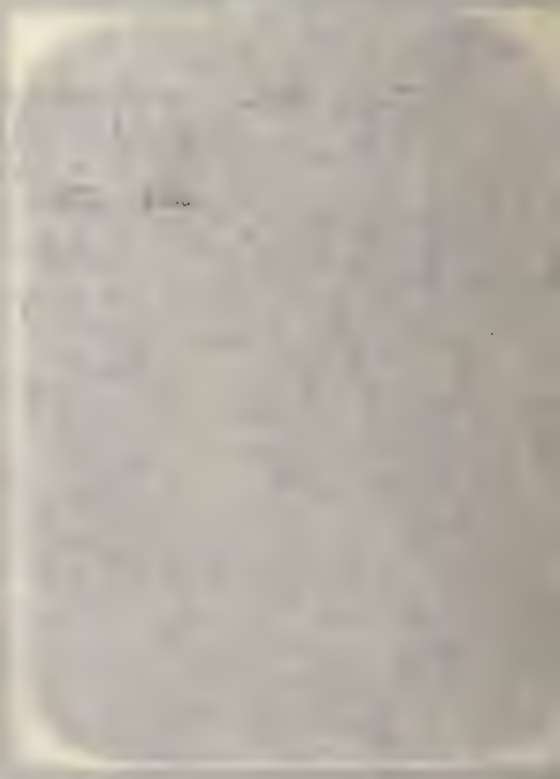


PLATE XXVII

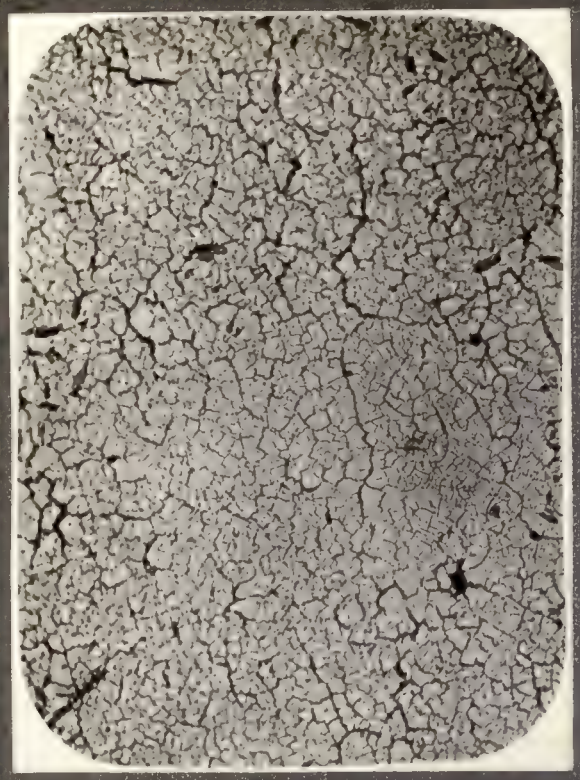
Photographs of Polished Surfaces of Ores from Kennecott, Alaska.

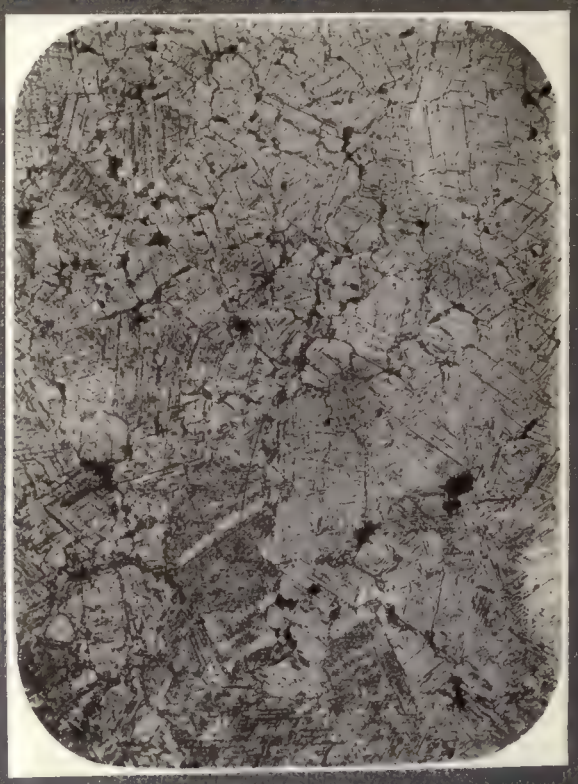
Fig. 105. (x 60 diameters) Bonanza Mine. Steely chalcocite, etched with nitric acid. There is a slight suggestion of the concentric structure of "pebbly chalcocite" in it, but the material is massive in the handspecimen.

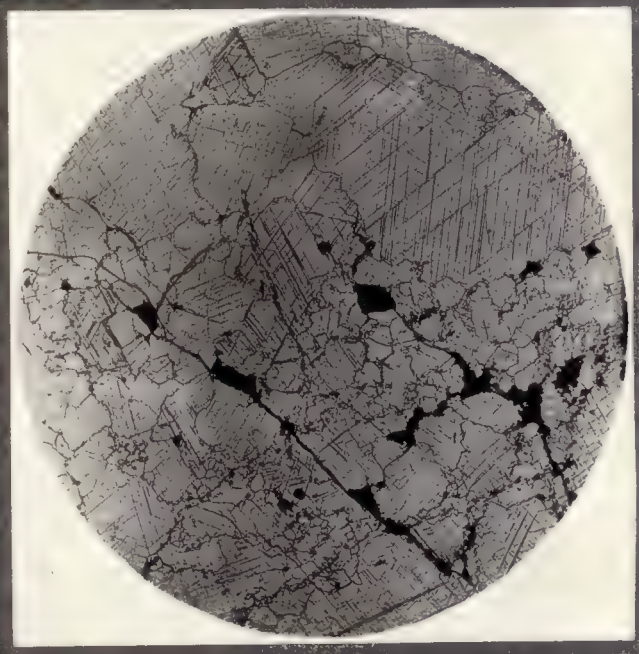
Fig. 106. (x 60 diameters) Chalcocite, etched with potassium cyanide solution, showing variation in grain, and the triangular etch-pattern in nearly all cases.

Fig. 107. (x 50 diameters) Chalcocite, etched with potassium cyanide, revealing triangular etch-pattern.

Fig. 108. (x 60 diameters) Chalcocite, etched with potassium cyanide solution.
For discussion of these etch-patterns, see pages 25 and 356.







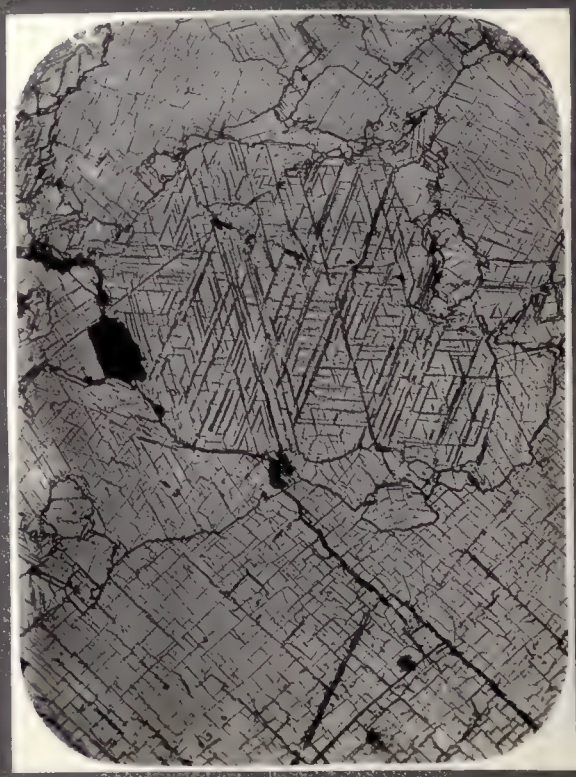


PLATE XXVIII.

Photographs of Polished Surfaces of Ores from Kennecott, Alaska.

Fig. 109. (x 280 diameters) Bonanza Mine. "Diabasic" covellite. Covellite (dark, mottled due to pleocroism), with chalcopyrite (white) and bornite (bn, light gray) between the covellite laths.

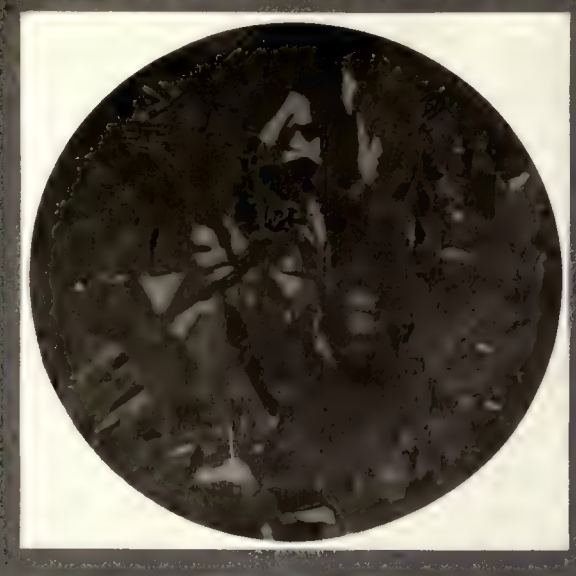
Fig. 110. (x 280 diameters) Bonanza Mine. "Diabasic" covellite. Covellite (dark), with chalcopyrite (white) and bornite (light gray) between the laths.

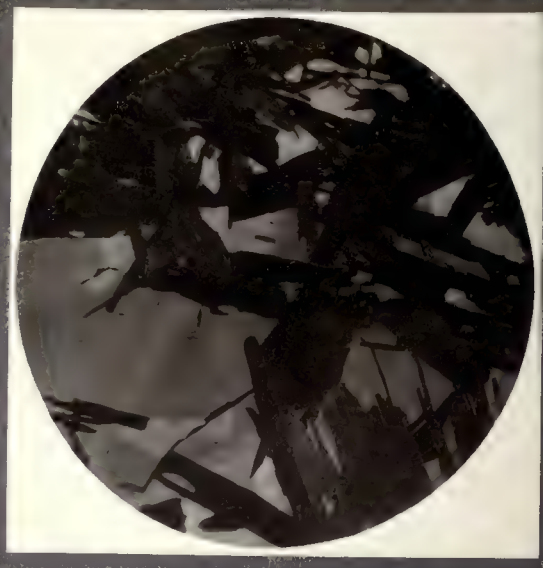
Fig. 111. (x 40 diameters) Bonanza Mine. Covellite plates in radial and scalloped patterns, partially replaced by chalcocite (white).

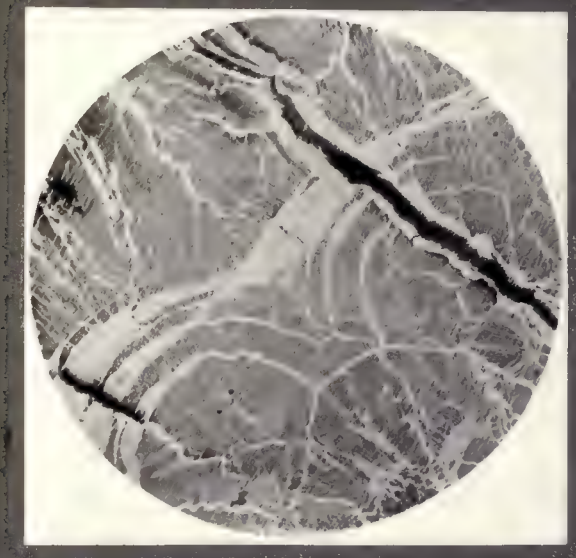
Fig. 112. (x 40 diameter) Bonanza Mine. From the same as Fig. 111.

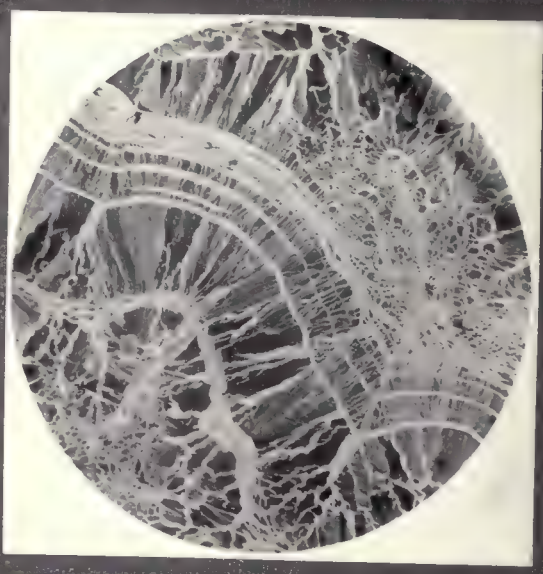
Fig. 113. (x 65 diameters) Bonanza Mine. Covellite (dark) in chalcocite (light).

Fig. 114. (x 50 diameters) Jumbo Mine. Complex aggregate of chalcopyrite and bornite in concentric structures. Partially replaced by covellite and luzonite (lightest). Coarser plates of covellite filling space between the curved masses of chalcopyrite and bornite.









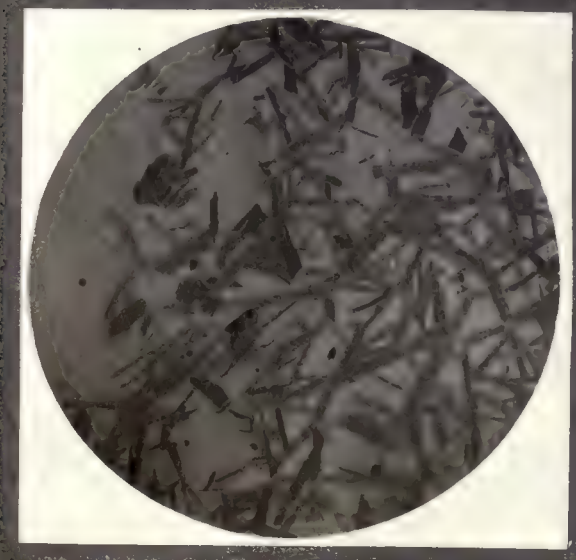


PLATE XXIX

Photographs of Polished Surfaces of Ores from Kennecott, Alaska.

Fig. 115. (x 280 diameters) Bonanza Mine. Bornite, etched with potassium cyanide solution, yielding brick-like pattern. Black squares and rectangles due to small blocks springing out between cracks of the etch structure.

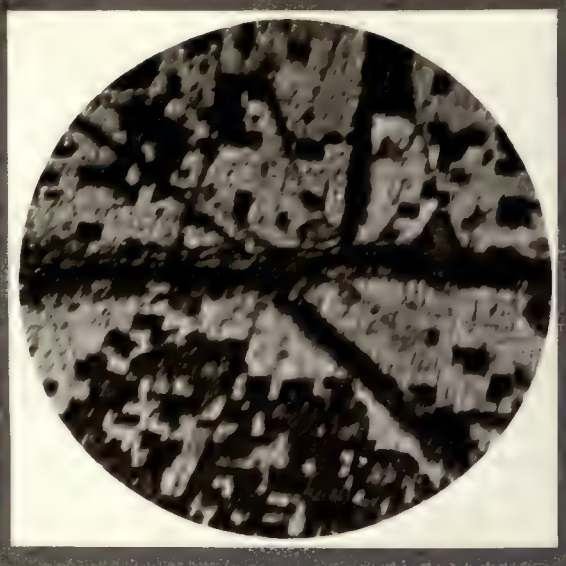
Fig. 116. (x 50 diameters) Erie Mine. Bornite (bn) and chalcocite (cc, almost the same color in this photograph), partially altered to malachite with intermediate covellite in the chalcocite. The triangular structure in the chalcocite and its absence in the bornite, as shown by the malachite veinlets, is noteworthy.

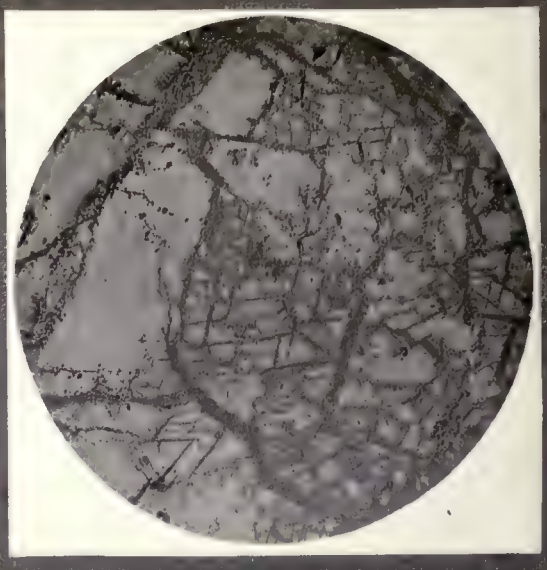
Fig. 117. (x 80 diameters) Bonanza Mine. Chalcocite altering to malachite along structural lines.

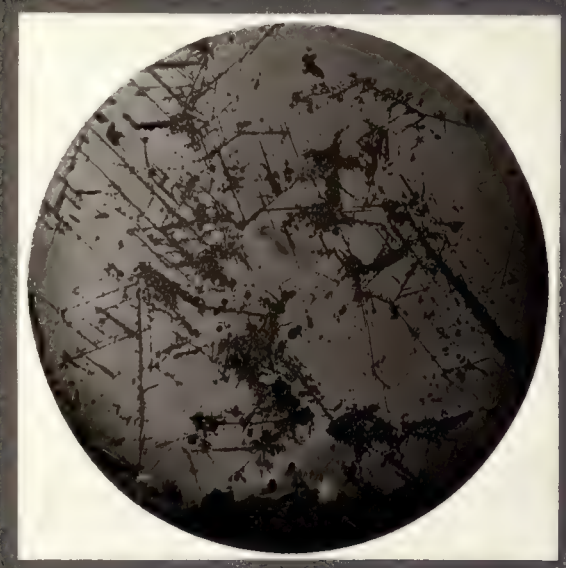
Fig. 118. (x 80 diameters) Erie Mine. Bornite (gray) partially replaced by chalcocite (light). Triangular structure shown by malachite veinlets in the chalcocite, but not in the bornite. Lack of chalcocite lattice in the bornite is noteworthy.

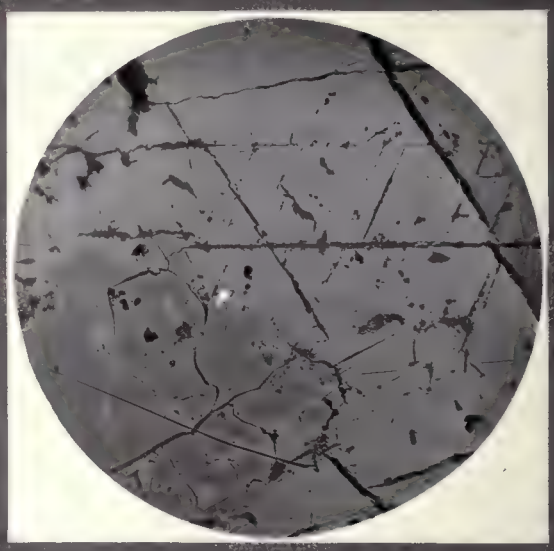
Fig. 119. (x 80 diameters) Erie Mine. Bornite (dark) partially altered to chalcocite (light) along irregular veinlets. The strips of white chalcocite in the blue type reveal the structure of the chalcocite. This structure is emphasized by malachite veinlets (black).

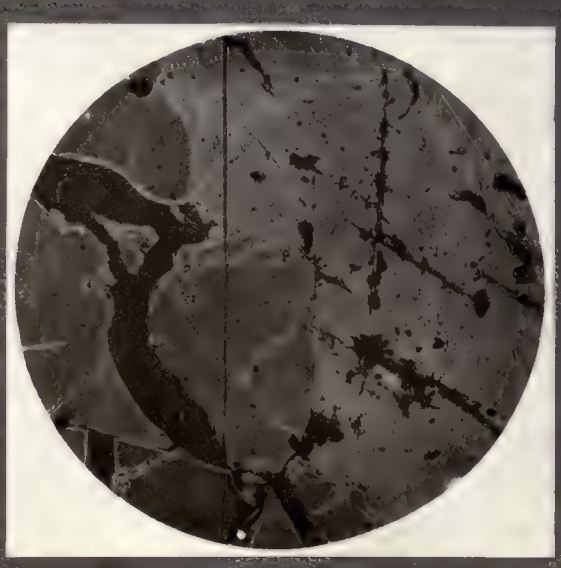
Fig. 120. (x 50 diameters) Erie Mine. Bornite (bn) and chalcocite (cc, somewhat lighter) in a large area and as ~~from~~ veinlets in bornite. Note contrast in structure developed by the malachite veinlets in the chalcocite and in the bornite.











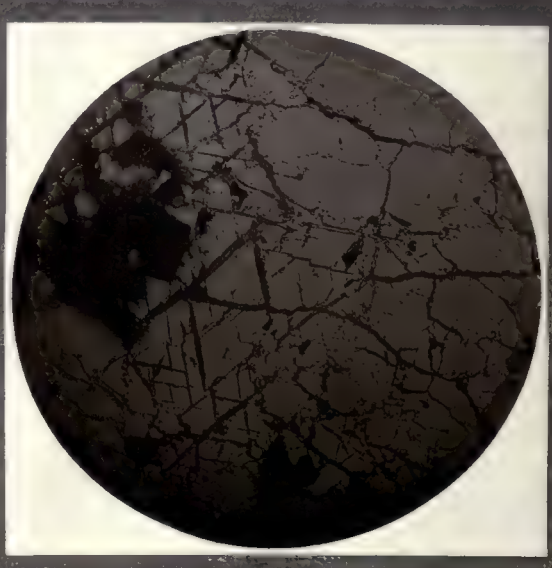


PLATE XXX

Photographs of Polished Surfaces of Ores from Kennecott, Alaska.

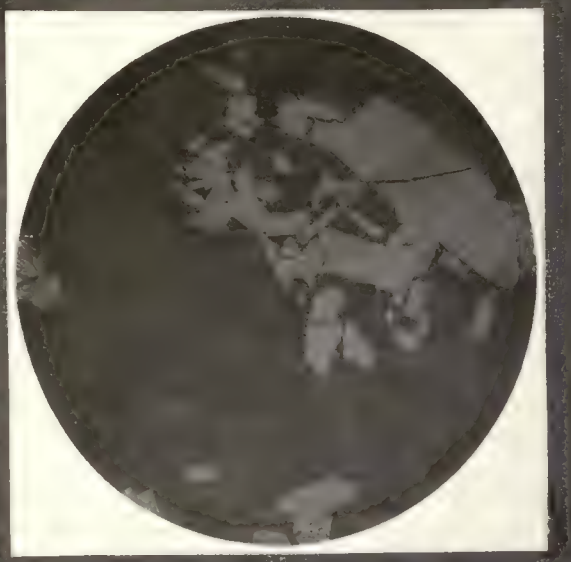
Fig. 121. (x 46 diameters) Bonanza Mine. Enargite crystals in limestone.

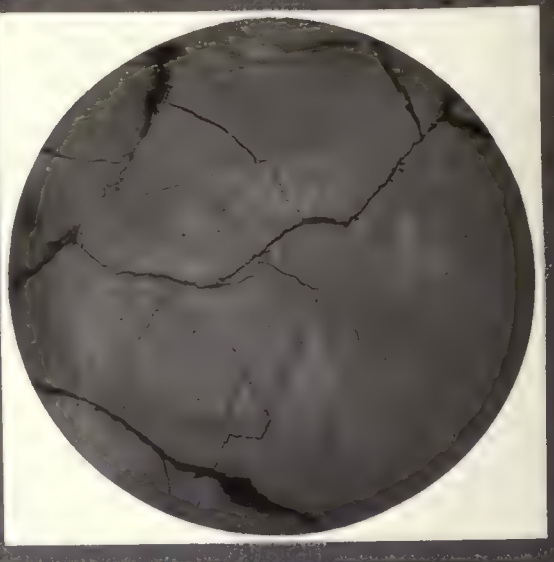
Fig. 122. (x 80 diameters) Jumbo Mine. Chalcopyrite (light of the earliest generation partially replaced bornite (darker).

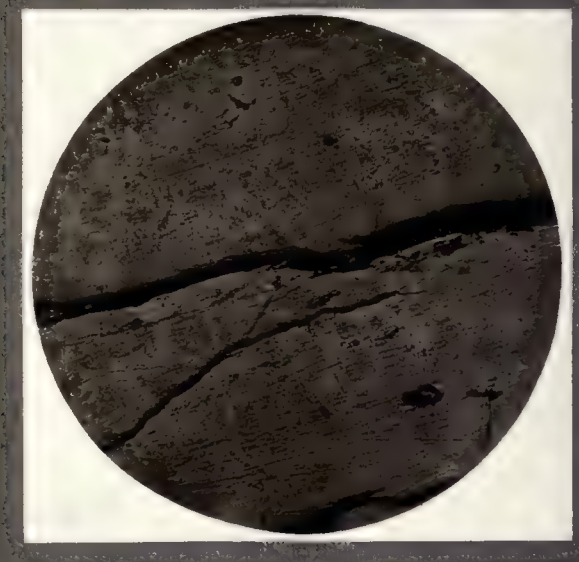
Fig. 123. (x 280 diameters) Jumbo Mine. Chalcopyrite of later age developing in bornite (dark) in part in feathery lattice structure.

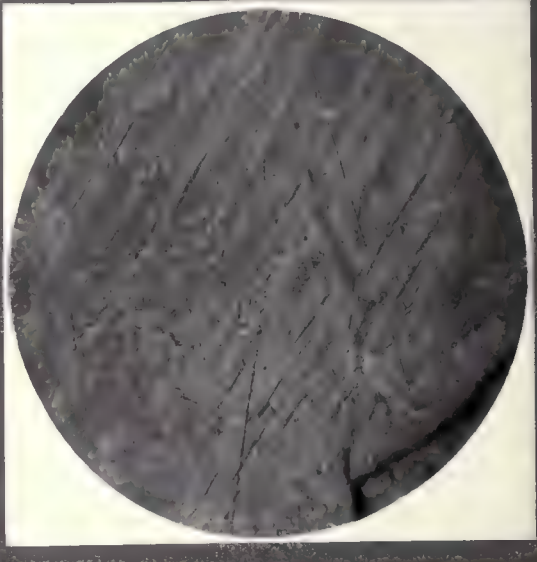
Fig. 124. (x 280 diameters) Jumbo Mine. Chalcopyrite (light) developing in feathery lattice structures in bornite (dark). Note the apparent resistance of the bornite in certain zones, often in vein-like strips with characteristic angular offsets.

Fig. 125. (x 80 diameters) Jumbo Mine. Bornite (dark) replacing chalcopyrite of the earlier generation (light).









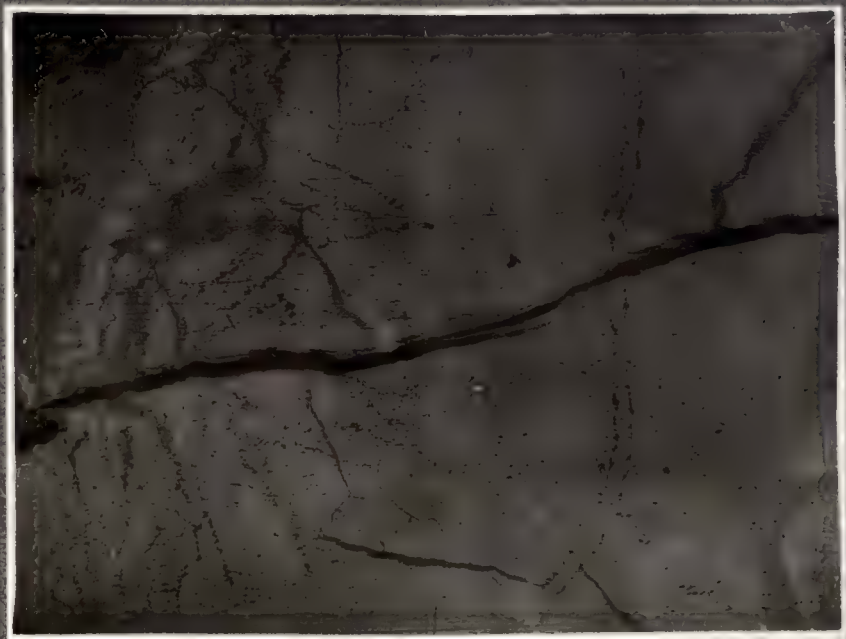


PLATE XXXI

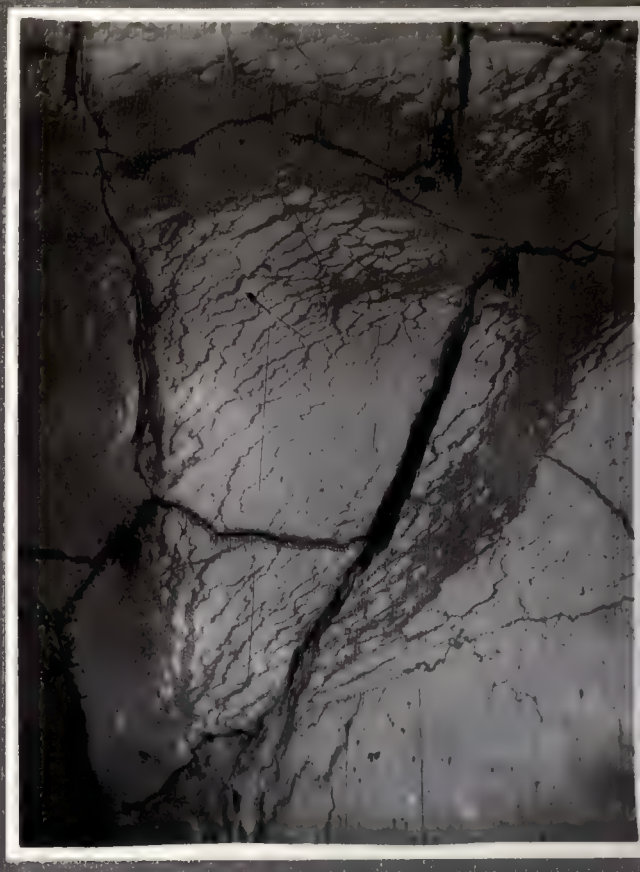
Photographs of Polished Surfaces of Ores from Kennecott, Alaska.

Fig. 126. (x 80 diameters) Jumbo Mine. Chalcopyrite (light) of the earlier generation, partially replaced by bornite (dark). Black lines are cracks in the polished surface.

Fig. 127. (x 80 diameters) Jumbo Mine. Similar to Fig. 126.

Fig. 128. (x 80 diameters) Bonanza Mine. Covellite (dark) partially replaced by chalcocite, (light). Two bands of bornite residues (slightly lighter) in the chalcocite. The specimen possesses a scalloped structure but it is not well shown in this part of the field. Veinlets of malachite in the chalcocite in one zone.

Fig. 129. (x 80 diameters) Bonanza Mine. Covellite (dark) in radial plates, partially replaced by chalcocite.



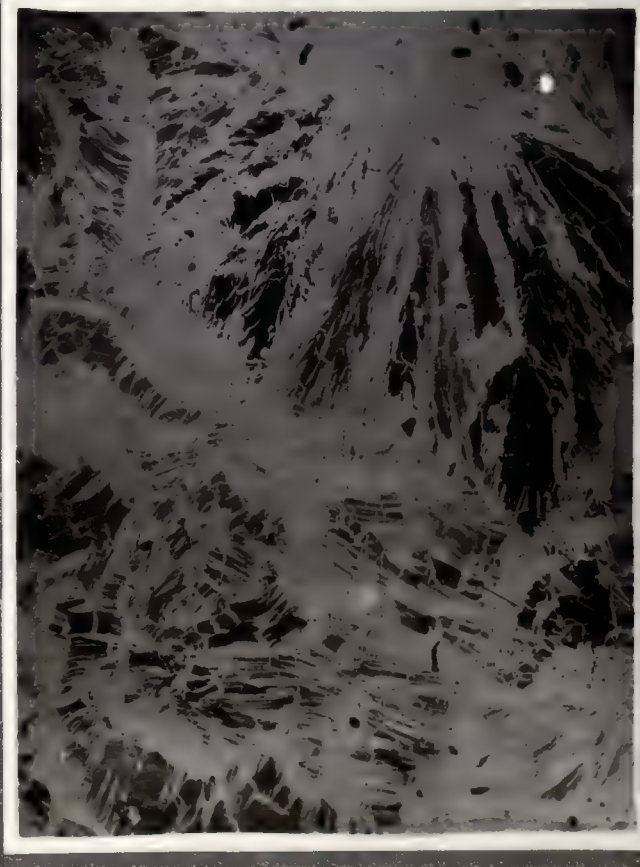


PLATE XXXII.

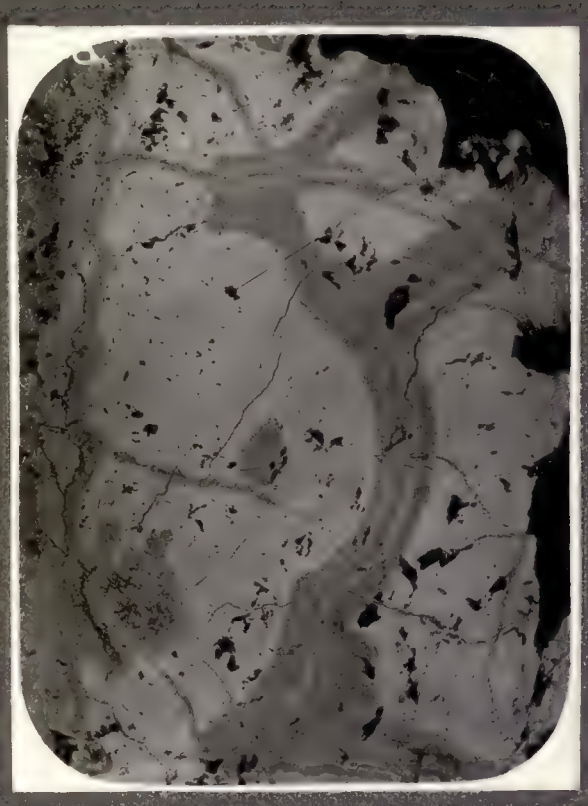
Photographs of Polished Surfaces of the Kennecott, Alaska.

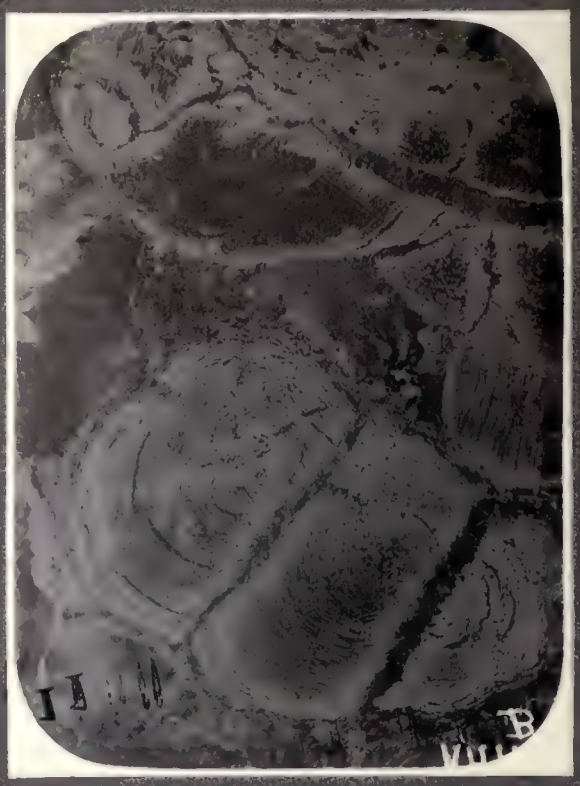
Fig. 130. (x 80 diameters) Bonanza Mine, open cut. Bornite (dark) and chalcopyrite (light) in scalloped structures. Broken by azurite veinlets.

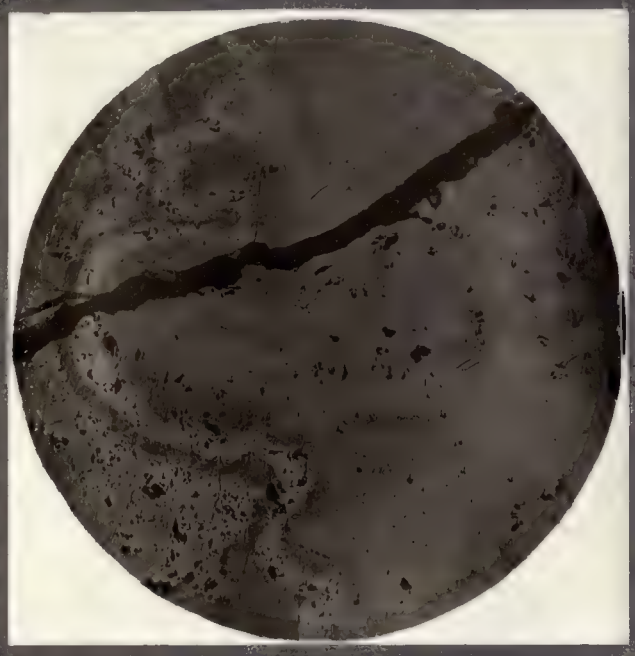
Fig. 131. (x 80 diameters) Jumbo Mine. Complex association of chalcopyrite (light), bornite (dark), and covellite (dark, mottled) in concentric structures. The covellite is largely a replacement of bornite.

Fig. 132. (x 50 diameters) Bonanza Mine, open cut. Chalcopyrite (light) and bornite (dark) with chalcocite (a little lighter than the bornite) in scalloped structures.

Fig. 133. (x 50 diameters) Jumbo Mine. Complex association of chalcopyrite and bornite in exceedingly intricate mass (mottled, light gray), with later luzonite (white) and covellite (mottled gray), in concentric and scalloped structures characteristic of certain "knots" in the ore. For discussion see pages 267 to 268. Crystals of bornite or chalcopyrite with rims of luzonite (?) occur on the right side of field. Covellite replaces bornite, and forms fringes of radial plates about margins of curved masses of the earlier minerals. The luzonite is in part later than the covellite.







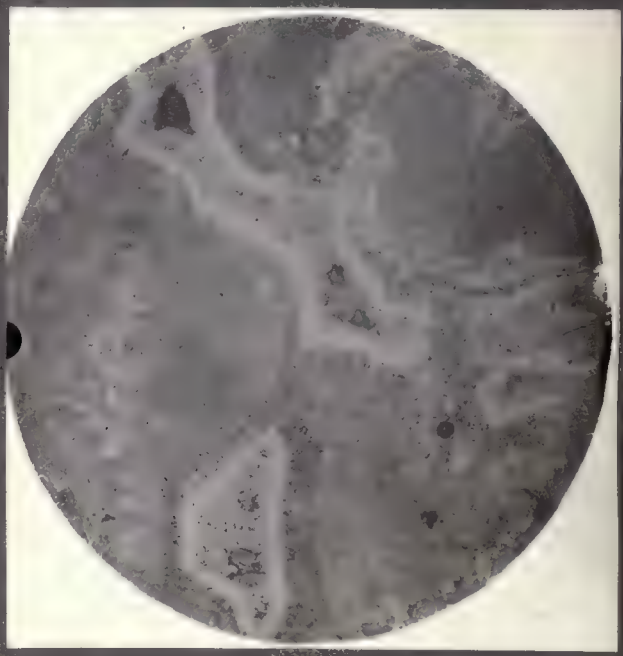


PLATE XXXIII

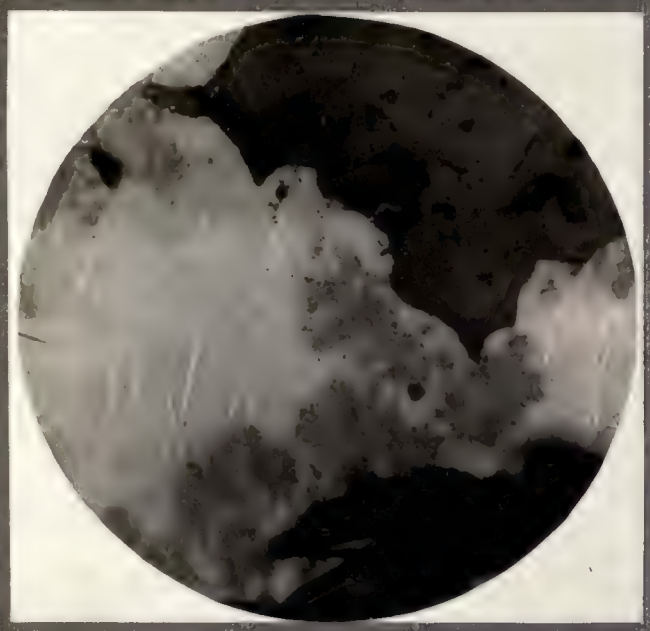
Photographs of Polished Surfaces of Ores.

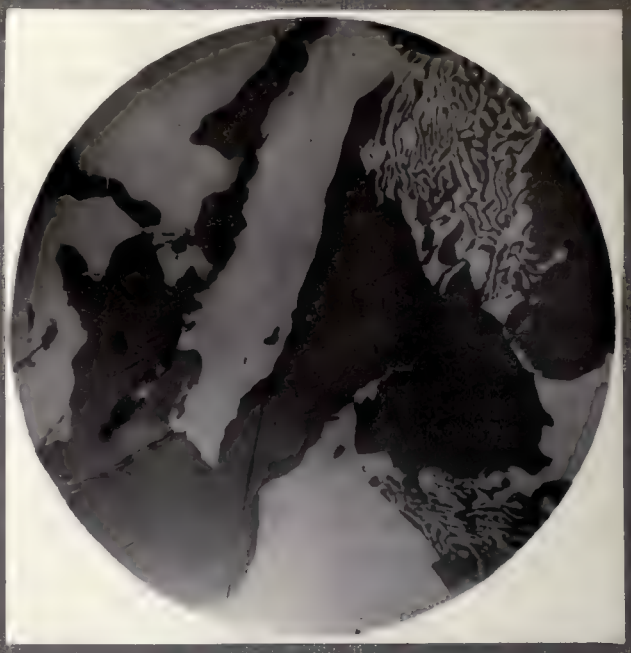
Fig. 134. (x 270 diameters) Ajo, Arizona. Chalcopyrite in lattice structure in bornite (light gray). Chalcocite and malachite (dark gray) around the margins of the grain. Gangue, black. Photographed by Murdoch.

Fig. 135. (x 80 diameters (?)) Virgilina, Virginia. Bornite (dark) with chalcocite (light) in graphic structures and associated with mutual boundaries. Photographed by Murdoch.

Fig. 136. (x 30 diameters (?)) Messina, South Africa. Bornite (light) and chalcocite (dark) in graphic structure. Etched with nitric acid showing the orthorhombic structure of the chalcocite, and its parallel orientation throughout the graphic pattern. Photographed by Alfred Wandtke.

Fig. 137. (x 750 diameters) Ajo, Arizona. Bornite (dark) with chalcopyrite (light), developed in lattice structure. Photographed by Murdoch.





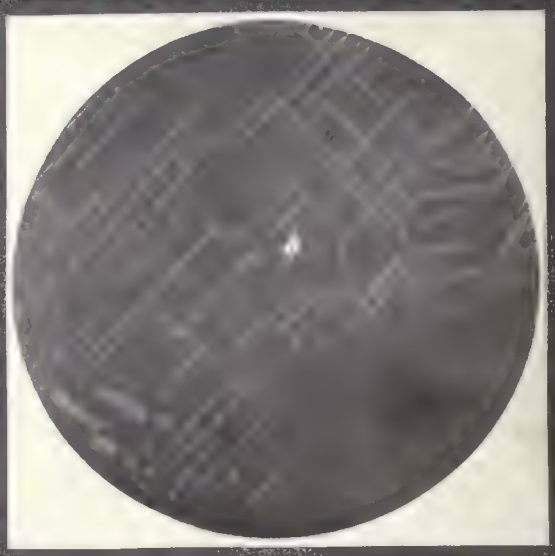


PLATE XXXIV

Photographs of Polished Surfaces.

Fig. 138. (x 65 diameters) Messina, South Africa. Chalcocite treated with nitric acid showing orthorhombic etch-pattern. Photographed by Alfred Wandtke.

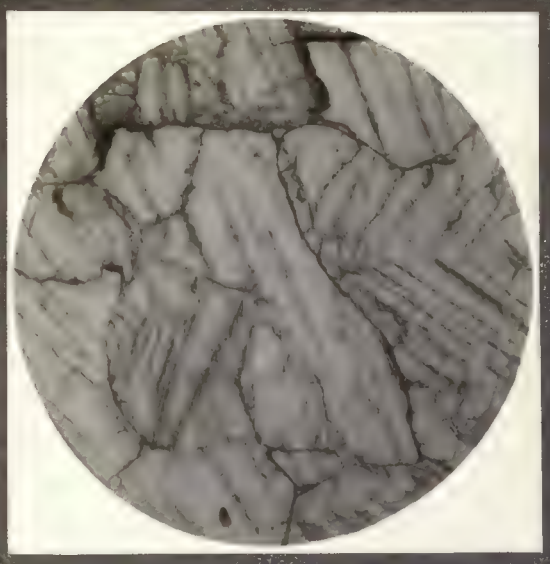
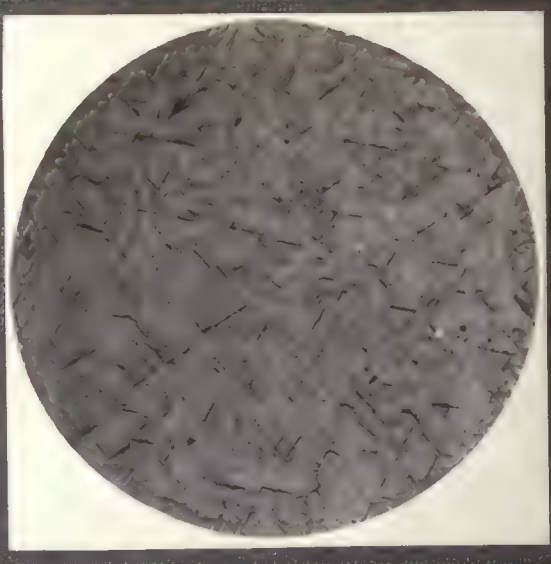
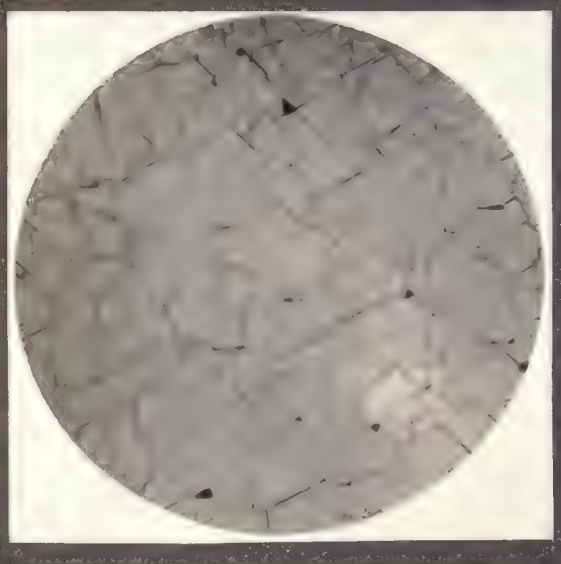
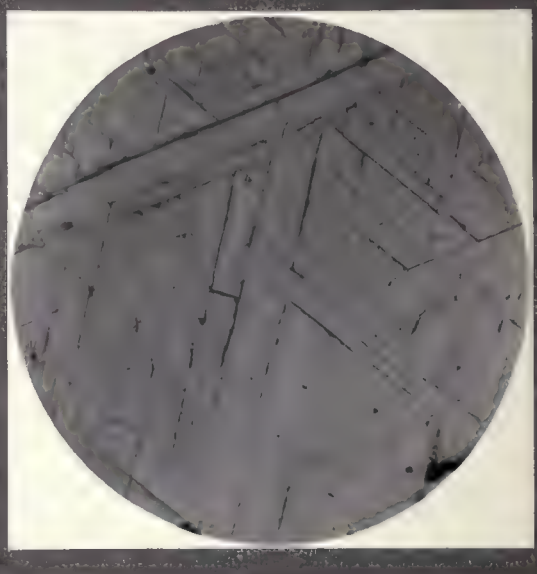
Fig. 139. (x 65 diameters) Synthetic chalcocite from the Geophysical laboratory formed above 91°C with an excess of sulphur. Etched with nitric acid, revealing the octahedral parting of the isometric high temperature chalcocite. This and the following microphotographs are by Murdoch.

Fig. 140. (x 65 diameters) Synthetic chalcocite similar to that in figure 139.

Fig. 141. (x 50 diameters) Similar to figures 139 and 140

Fig. 142. (x 70 diameters) Butte. Bornite (dark) with chalcocite (light), possessing a blue and white lattice, suggesting replacement of bornite through the lattice stage.

Fig. 143. (x 45 diameters) Butte. Splines of bornite (dark) in chalcocite (light) and broken by irregular veinlets of chalcocite.

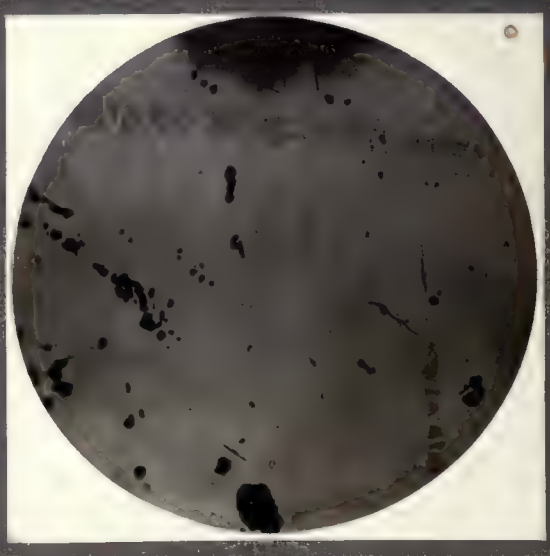


PLATE XXXV

Photographs of Polished Surfaces of Ores.
(Murdoch).

Fig. 144. (x 65 diameters) Butte, Montana. Chalcocite (white) with bornite (dark) along margins of grains, and "spot structures" in the adjoining chalcocite grains.

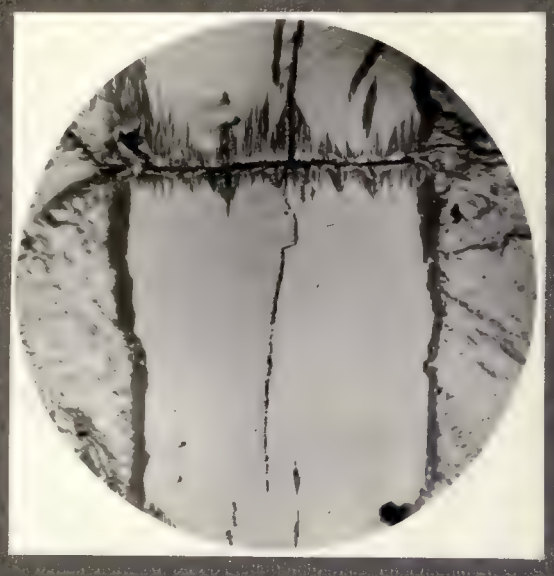
Fig. 145. (x 340 diameters) Butte, Montana. Spot structures, and subgraphic structures, between bornite (dark) and chalcocite (light). Note curved, banded distribution of the bornite specks.

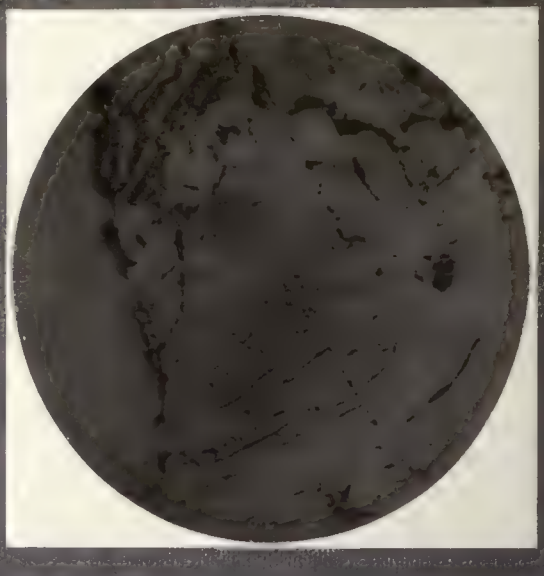
Fig. 146. (x 65 diameters) Butte, Montana. Bornite (dark) with chalcocite (light) in the lattice pattern. Note the resistant rim of bornite along the left of the grain.

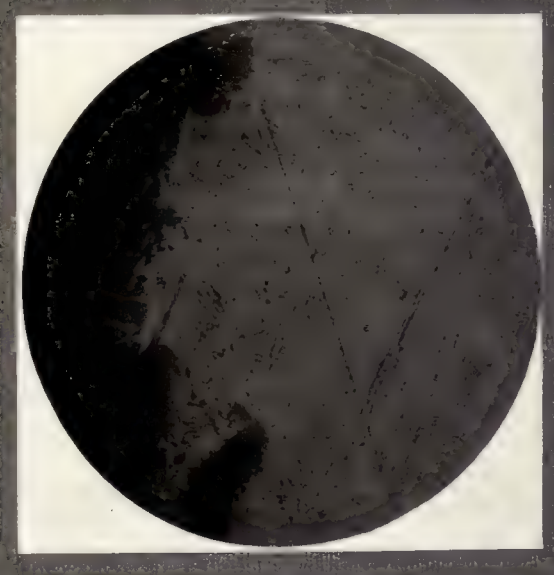
Fig. 147. (x 65 diameters) Splines of bornite (dark) remaining in a field in which the bornite is largely replaced by chalcocite (light) in the lattice structure. The splines, however, are slightly replaced by chalcocite in veinlets, developed parallel to the lattice directions.

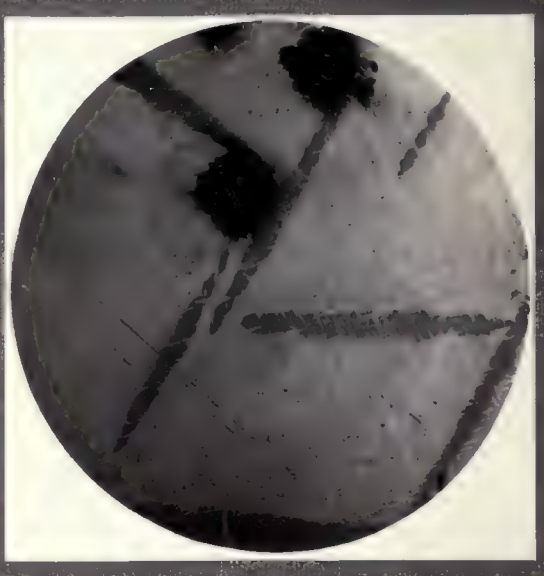
Fig. 148. (x diameters) Bonanza Mine, Kennecott, Alaska. Bornite (dark) partially replaced by chalcopyrite (light), developed in the lattice pattern. Bornite splines remain little altered.

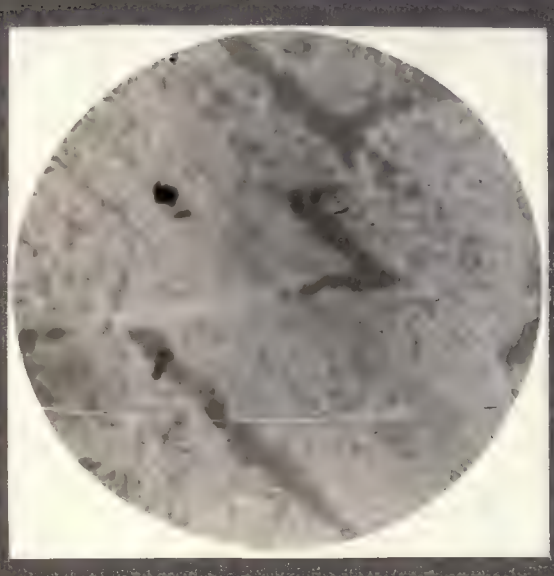
Fig. 149. (x diameters) Butte, Montana. Bornite spline in a field of bornite-chalcocite lattice, showing incipient alteration to chalcocite parallel to the lattice directions.











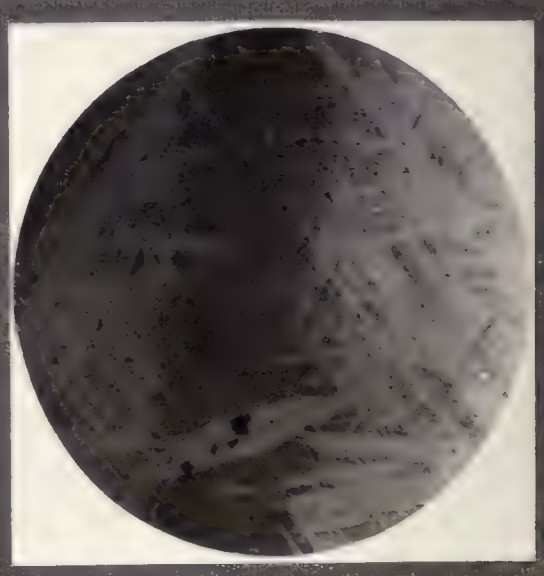


PLATE XXXVI

Photographs of Polished Surfaces of Ores.
(Murdoch).

Fig. 150. (x 65 diameters) Redruth, Cornwall. Bornite (dark) along cracks in chalcocite (light).

Fig. 151. (x 135 diameters) Redruth, Cornwall. Similar to Fig. 150. The relations elsewhere and the structure of the chalcocite indicates that the chalcocite is a replacement of bornite. The preservation of these veinlike strips may possibly be due to outgoing iron. Chalcopyrite frequently occurs along their centre lines.

Fig. 152. (x 150 diameters) Copper Queen, Bisbee, Ariz. Bornite (dark), partially altered to chalcocite (light), which develops the lattice structure in the bornite.

Fig. 153. (x 50 diameters) Calument and Arizona Mine, Bisbee, Arizona. Chalcopyrite grains with halos of bornite in a field of chalcocite. Cores of pyrite in a few cases.

Fig. 154. (x 115 diameters) Bonanza Mine, Kennecott, Alaska. Bornite (dark) partially replaced by intricate chalcopyrite lattice (light). Vein-like strips of bornite remain, which at this magnification make it seem certain that the sequence is the reverse of that stated. For discussion, see page 259.

Fig. 155. (x 40 diameters) Butte, Montana. Bornite (light gray) partially altered to covellite (dark) along veinlets, with adjacent chalcopyrite (white) and pyrite (rough, with high relief) untouched.

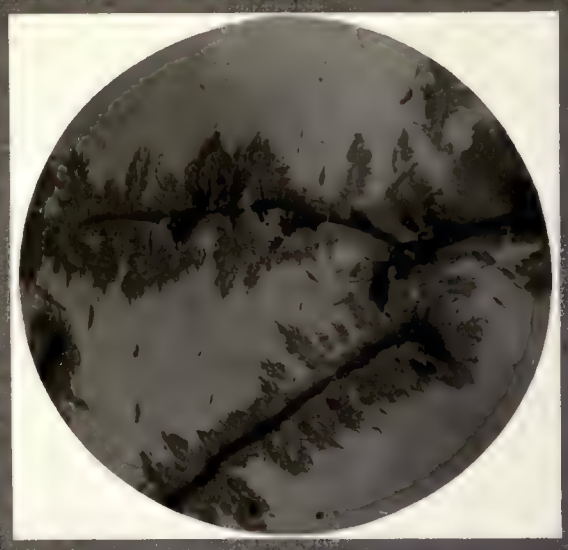
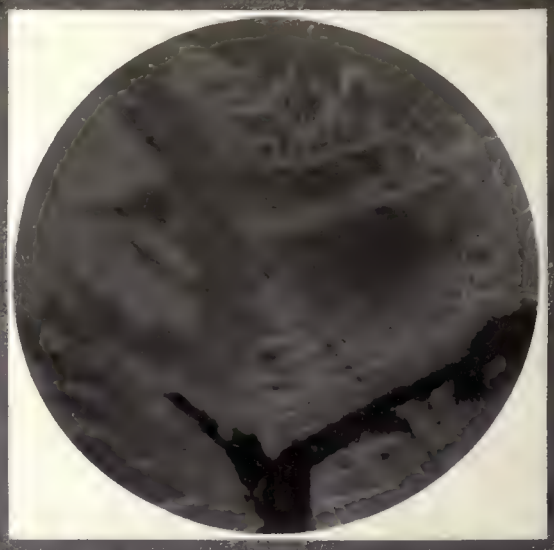
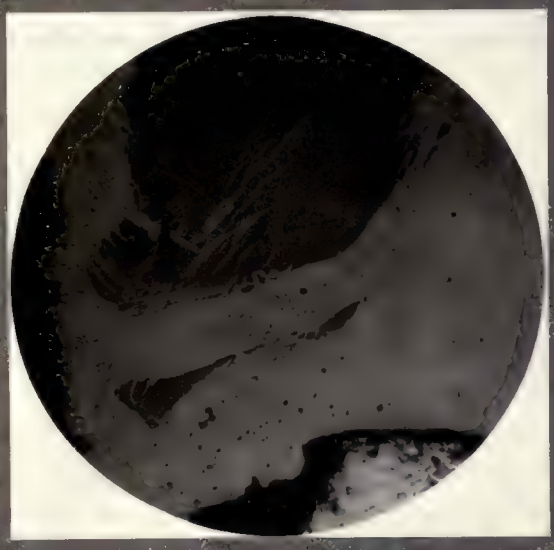
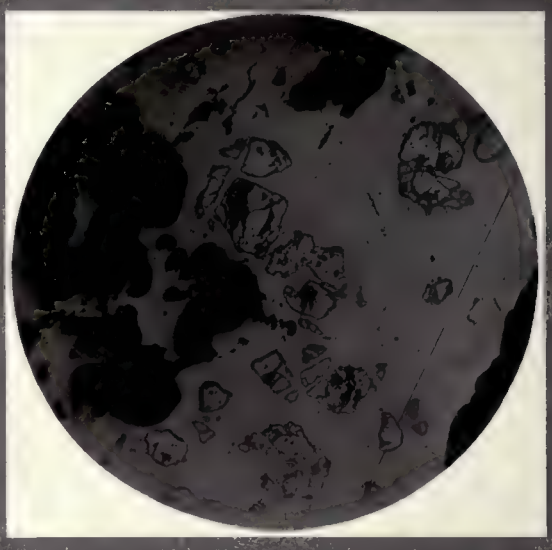
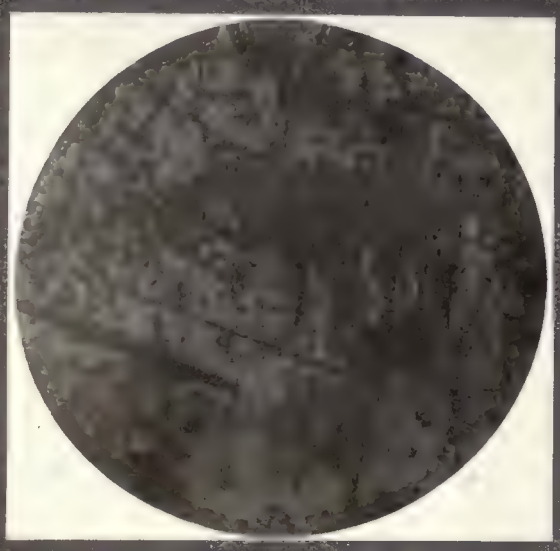
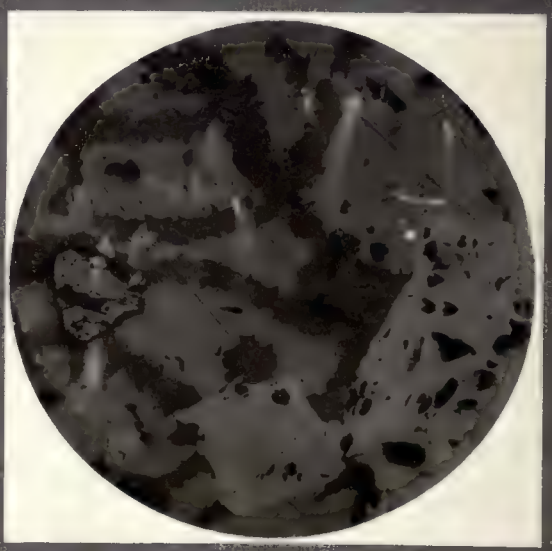







PLATE XXXVII

Microphotographs of Polished Surfaces of Ores from Shasta Co., California.

(Photographed by J. Murdoch)

Fig. 156. (x diameters) From Sutro Mine. Bornite (dark) and chalcocite (light). The chalcocite possesses a grained structure and a mottled appearance shown by the variation in color on the polished surface. Note minute subgraphic forms of the bornite in the chalcocite.

Fig. 157. (x diameters) From Sutro Mine. The same field as in figure 156, but etched with nitric acid, revealing the orthorhombic nature of the chalcocite, and showing the different orientations of the individual chalcocite grains. The fine lines of the etch-pattern of the bornite are shown faintly, especially on the right side of the chalcocite field, and the structure is emphasized by the characteristic blocks which have sprung out between the cracks.

Fig. 158. (x diameters) From Sutro Mine. Bornite (dark) and mottled chalcocite (light) in relations similar to those shown in figures 156 and 157.

Fig. 159. (x diameters) From Afterthought Mine. Calcite (black), partially replaced along its cleavages by bornite (grey) and chalcocite (light). The chalcocite is believed to be a replacement of bornite.

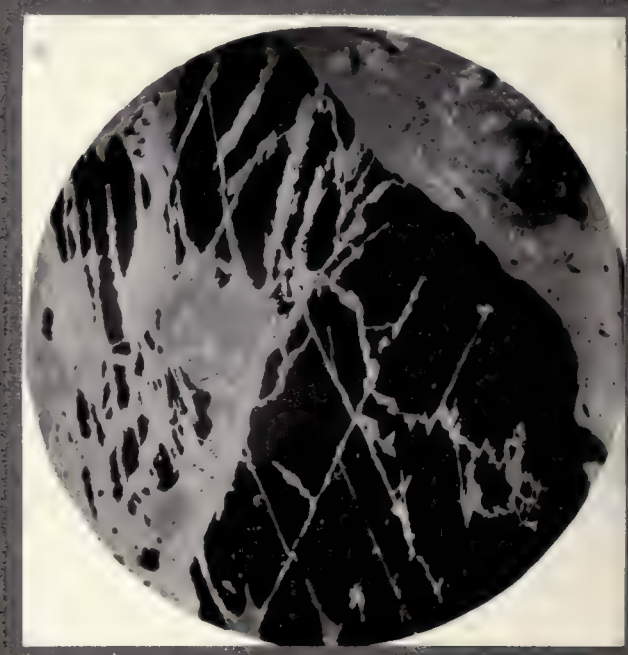


Plate XXXVIII.

Photographs of Polished Surfaces of Ore.
(Photographed by Murdoch).

Fig. 160. (x diameters) Butte, Montana. Chalcopyrite (white) developed in bornite (dark) in the lattice structure.

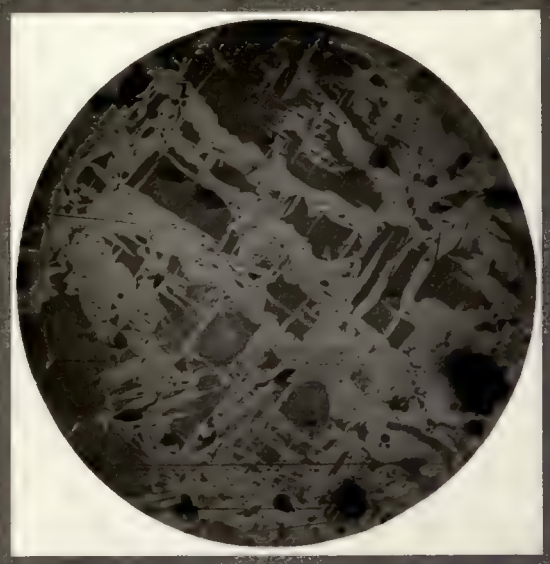
Fig. 161. (x diameters) Butte, Montana. Chalcopyrite (white) developed in bornite (dark) in part in the lattice structure.

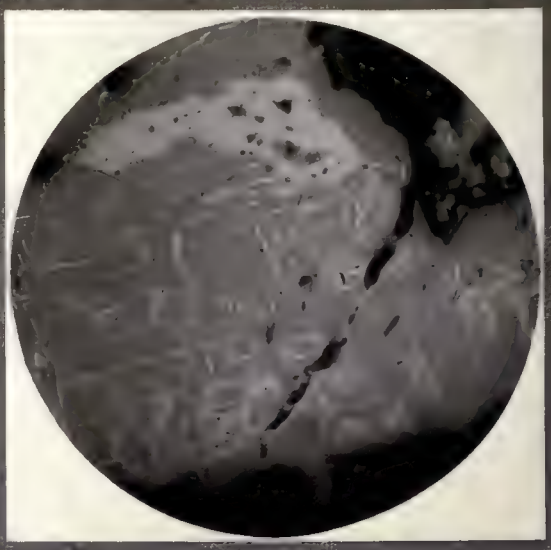
Fig. 162. (x 45 diameters) Artificial products close to chalcopyrite and bornite in composition, crystallized from a melt in the Geophysical Laboratory. (chalcopyrite, light; bornite, dark).

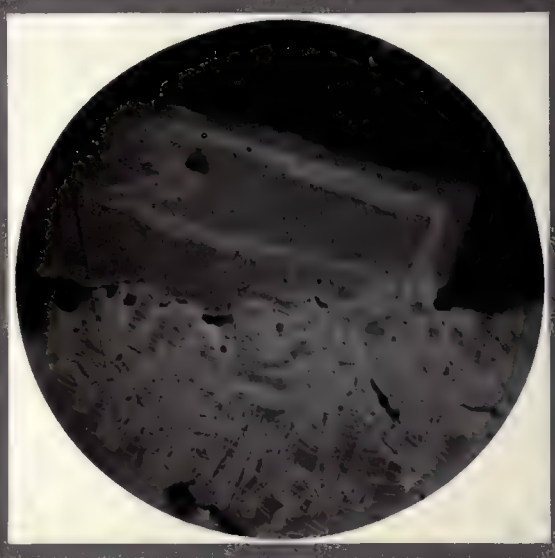
Fig. 163. (x 85 diameters) Redruth, Cornwall. Bornite crystal containing symmetrically distributed chalcopyrite in the lattice structure.

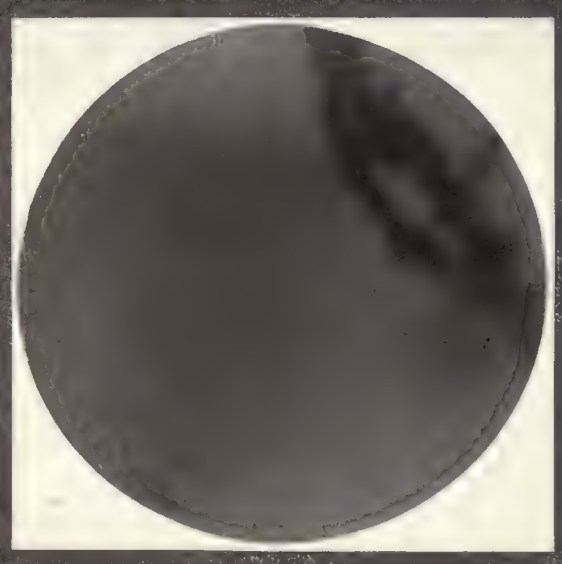
Fig. 164. (x 770) Seven Devils, Idaho. Exceedingly fine lattice of chalcopyrite in bornite.

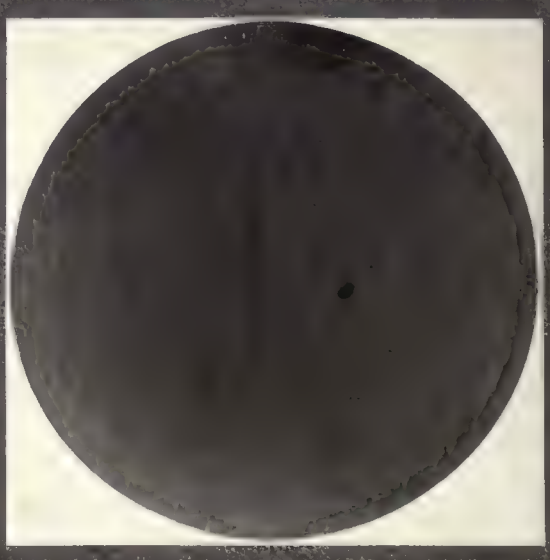
Fig. 165. (x 770) Seven Devils, Idaho. Exceedingly fine lattice of chalcopyrite in bornite.











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